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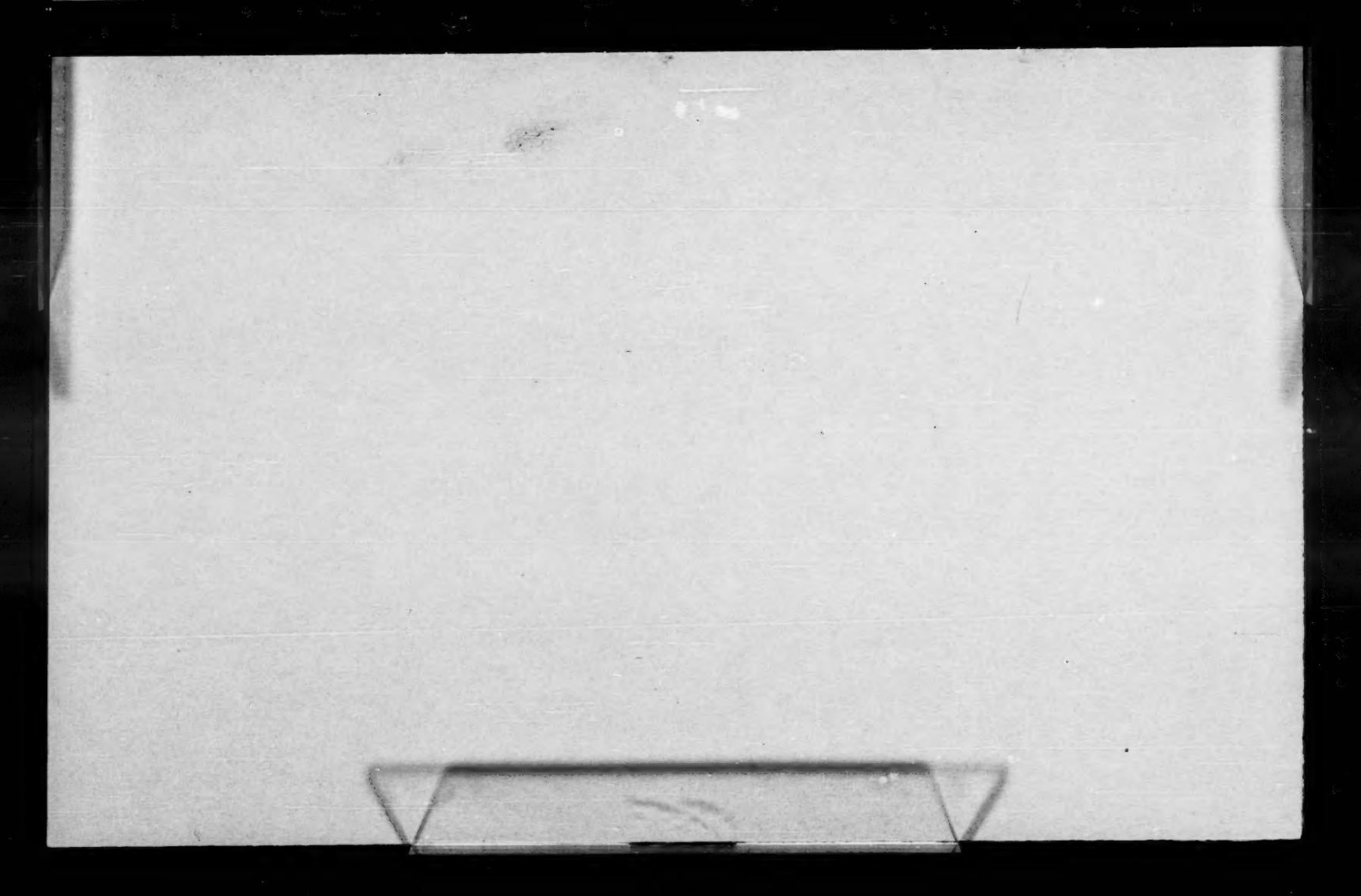

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ISOSTASY AND THE ORIGIN OF SIAL AND SIMA AND OF PARENTAL ROCK MAGMAS*

WALTER WAHL

INTRODUCTION

ALTHOUGH much has been written by geophysicists and geologists on isostasy and isostatic adjustment of portions of the earth's crust, the geochemical consequences of isostatic adjustment have so far not been dealt with. This is rather surprising, since it is quite evident that the vertical change of position of rock masses brought about by isostatic adjustment will bring large masses of rock into new environments where temperature and pressure are entirely different from those under which they were formed and can remain stable, and where therefore changes of chemical equilibrium and even melting to a smaller or larger degree will take place. Thereby, necessarily, considerable geochemical changes are brought about, and these, in combination with the downward movements of portions of the earth's crust and with the rise of magmas from the deeper parts of the crust to the earth's surface, will bring about a vertical circulation of matter on a large scale in the outer parts of the earth's crust. It is the aim of the author to discuss in this paper the geochemical processes originating and taking place on account of isostatic adjustment and its extreme consequences as they manifest themselves in orogenic zones.

In a recent publication, Vening Meinesz (1948) has summarized present thought on the formation of geosynclines and on orogenic movement in the following short and lucid way: Vening Meinesz says (p. 194):

"I shall here adhere to the interpretation that the folding and overthrusting of the surface layers are the accompaniment of a

* An abstract of part of this paper was given as a lecture at the Geochemical Section of the 18th International Geological Congress in London, 1948.

great compression of the whole crust of the earth which causes a downward buckle of the crust in such a way that a great bulge is formed at the lower boundary of the crust. This bulge replaces the heavier subcrustal matter and thus represents a considerable deficiency of mass." — "The buckling limit being exceeded, the crust forms one or more waves of a few hundred kilometers in length and thus a geosyncline comes into existence, which leads to sedimentation. The process continues by means of a stronger deformation of the main downward wave which gradually forms the downward bulge described above. Incompetent surface layers are squeezed out and form folds and overthrusts at the surface." — "The further history of the geosyncline would, in outline, be as follows. We may assume that, after one or more periods of strong compression characterized by folding in the main belt, compression in the crust would decrease, and this would allow the affected area of the crust to detach itself, more or less completely, from neighbouring areas, and by rising to readjust, at least partially, its isostatic balance. This process would continue until the stage would be reached of a mature mountain range in isostatic equilibrium, as we know it in several existing mountain systems. Possibly the process would be accompanied by another one, that of the partial melting of the sialic root which, by the down-bulging, has been pressed below its normal level. We may assume that this fused matter would distribute itself below the crust and thus the root, so far as it did not disappear, would become broader and less deep."

We may add that during and after the reduction of the mountain range by erosion the underlying portion will be raised, and ultimately a peneplain is formed, which being in isostatic equilibrium, will consist of the old, formerly deeply submerged roots of the mountain range.

As the study of the great continental basement complexes of the world considered to be Archean has progressed, it has gradually been recognized that these complexes contain much material that is unquestionably composed of sedimentary and volcanic material originally formed at the surface of the earth, which material has later, by metamorphic processes, acquired its present gneissic character. The trend of thought of the school of Lyell, especially as later on developed by Sederholm, gradually gained more and more ground and an "actualistic origin" of the "Archean basement" has become generally admitted.

The rocks originally formed in an "actualistic" way have by becoming folded and overthrust been moved to great depths where remelting has taken place, in some cases of only the earlier melting or soluble portions, in other cases—when sufficient depth and temperature have been reached—of the greater portions or even the entire mass. Where we now find "the Archean" exposed it always shows signs of having been subjected to orogenic forces, and we now describe parts of it as having been formed during such or such period of mountain folding, as for instance when we in Fennoscandia speak of the rocks of the "Svecofennian Archean mountain chain." Other parts of the Archean basement here we consider to have been formed during other periods of orogenesis, in part older, in part younger than the Svecofennian movement.

It becomes more and more evident that what we are able to study of the Archean basement to a great extent belongs to what we may classify as roots of old mountain chains, the material of which has been subject to at least partial remelting or resolution or a combination of both these processes. The rock material now contained in these basement complexes has at one time, or at several times, been forced down to great depths in the earth's crust and subsequently by isostatic adjustment brought back to its present position at the surface of the earth's crust, taking part during these movements in the vertical circulation of matter in the earth's crust.

THE GEOCHEMICAL CONSEQUENCES OF ISOSTASY AND ISOSTATIC ADJUSTMENT

When the rock material either deposited by sedimentation in a geosynclinal trough or forming the basement supporting such a geosyncline is, during the development of the geosyncline and subsequent orogenic movement, forced downwards, generally to great depth, this rock material becomes exposed to temperatures and pressures entirely different from those under which it was originally formed. During movement downward of the rock material it will first undergo such kinds of metamorphosis as are consistent with the conditions reigning in the depth zones into which it enters, the well known stages of metamorphism described by Becke, Grubenmann and Niggli being passed through, and also the "facies" changes of Eskola. All the important changes that the rock material will

undergo are now well known through the work of the authors mentioned above and others, and we shall not here enter upon details, but instead try to find out what happens when the rock material moves downward to depths and temperatures where the rocks begin to soften and still further down to melt.

When melting of a rock composed of several minerals sets in, it will in the case of an igneous rock start very much in a similar, though reverse, way to that in which crystallization of the rock finished when the rock was formed. That is to say, in a granite or a granodiorite the potash and soda-rich feldspar portions, and what they are able to dissolve of the quartz and the femic minerals present, will be the first parts to be liquified, and they will also absorb most of the volatile matter such as enclosed water vapor. A granitic magma will result, which at the tensions and conditions of shear existing will be squeezed out.

In a lecture given before the Geological Society of Helsingfors in 1918 the present author discussed the influence of stress on the metamorphism and partial melting of rocks (Wahl, 1918). Since only an abstract in the Swedish language has been published, a short review of the conclusions arrived at is given here:

A fundamental difference exists between a uniform hydrostatic pressure and a unilaterally acting stress. Hydrostatic pressure raises the melting point of most solids, whereas stress lowers it, and mostly to a greater extent than it is raised by uniform pressure.

In a rock which becomes exposed to strong stress, the melting points are reached much earlier for some of its minerals than for others, and especially much earlier for the later crystallized portions of the mixed crystals than for those crystallized earlier. To take an example, the portion rich in albite of a plagioclase will under the combined action of heat and stress melt earlier than the more anorthite-rich portions, which may remain unmelted.

Since a rock during the action of stress is to begin with foliated at right angles to the action of the pressure, the albite-rich portions of plagioclases together with potash feldspar and quartz which they are able to dissolve will, as soon as their limit of melting is reached, be squeezed out along the foliation planes. The resulting product is then a banded rock, from which more or less of the most easily molten portions of the rock, depending on the amount of stress and on how soon the stress has been released, to a greater or lesser extent have been squeezed out. Also depending on how

soon stress is released and "regelation" sets in, the molten portions will either crystallize more or less "in situ" between the foliation planes of the rocks from which they were produced ("venites" of Holmquist) or be squeezed entirely out of the mother rock and enter the foliation planes of surrounding colder foliated rocks, forming "lit-par-lit" injections ("arterites" of Sederholm). In the latter case the gneisses remaining as residues after the squeezing out of the early melting portions will be of a much more femic character (hornblende-mica gneisses) than the original rock from which they were derived by this kind of stress-metamorphism.

Considering the general conditions in the deeper parts of the earth's crust, we may assume that, depending on conditions of depth, temperature, and stress, all gradations between "stress metamorphism" and "palingenesis" by heat action alone may occur.

A sedimentary rock or a gneissose rock containing alkali feldspars will behave very much in the same way, the alkali components, the feldspars, melting first and dissolving a certain amount of quartz and a little of femic components, forming what has often been called a "granitic eutectic." Quite generally we may say, that in any kind of rock containing alkali feldspars these will, at a certain depth in the earth's crust, start melting and a granite magma will begin to form, which, on account of its density being less than the still solid remainder of the rock, will be forced upwards.

The "palingenic" magmas originating in this way will, however, not possess much eruptive power, since they have not acquired temperatures much above their temperatures of solidification. They will therefore not be able to rise high in the earth's crust, but will probably only be able to impregnate the rock at some distance above the level from which they originate.

When the rock residues, after expulsion of the granite components, are moved downwards by further isostatic adjustments to still greater depths, there may be partial melting of the oligoclase-rich portions of the plagioclases and the dissolving of certain amounts of quartz, if such is still available in the rock residues, and also of part of the femic constituents, especially of the components rich in iron. The magma forming in this zone will be comparatively rich in femic components though a considerably "dryer" magma than those forming in a zone higher up, since these have already carried with them most of the volatiles available. Perhaps the intermediate

magmas of the "charnockite series" are formed in this way, and later, while ascending, are differentiated in the series charnockite, hypersthene syenite, and hypersthene diorite.

The remaining rock mass consists now chiefly of plagioclase, pyroxene, hornblende, mica, and magnetite, forming hornblende and mica gneisses and hornblenditic gneisses. These rocks will probably, for some distance in depth, be stable and remain as such. A proof hereof is that in the granites of the basement complexes of Fennoscandia, associated with migmatites, we often find xenoliths of hornblende gneisses in which the hornblende and mica show fairly little effect of alteration or melting. At a certain depth and temperature, however, break-down of the hornblende and mica molecules will take place and a considerable quantity of volatiles will anew be freed in this temperature zone. The material, being partly molten in this zone, will principally consist of the albite portion of the plagioclase together with iron and magnesium-silicate compounds from the broken down hornblende, giving rise to the sodium-, magnesium- and iron-rich magmas containing much volatiles that we know as the "spilitic magmas."

The remaining material of the original rock ground will then at still greater depths adjust itself to a "facies" that is stable. Ultimately we may have eclogites (Fermor, Eskola), and still farther downward, when these melt, the corresponding magmas of basaltic—peridotitic character, forming the lower part of the sima.

It may here briefly be pointed out that for the sake of simplicity it has in the preceding discussion been assumed that all the potash and most of the soda have been expelled above the temperature surface limiting the depth in which granites can exist. A certain amount of both potash and soda will, however, of course be held in solution by the femic components of the residues, and the sima will thus retain a certain small amount of the alkalies.

The further question arises how far downward in the sima shell will this partial melting of the material and the rising of the molten portion upwards in the earth's crust go on? Will it continue as long as there remains any simatic crystallized silicate shell or will it cease earlier? Eskola (1936) has pointed out that when the peridotitic part of the sima shell partially melts the portion rich in iron silicate will become

liquid and that this, being heavier than the magnesia-rich portion that remains crystalline, therefore ought to sink. However, conditions are actually more complicated, as we shall see presently.

When melting begins in a mixed crystal of forsterite (Mg_2SiO_4)—fayalite (Fe_2SiO_4), fayalite-rich melt will be produced. This is denser than the residue when this also is molten, but not necessarily denser than the remaining crystalline residue, which also is still rich in fayalite silicate. In the earlier part of the partial melting of a peridotite, an iron-rich silicate melt thus will be produced that will rise in the earth's crust, but gradually the remaining material will become less dense and at a certain composition the resulting molten portion and the remaining crystalline portion of the mixed crystals of the peridotite will have the same density and the molten portion will no longer rise in its surrounding of unmelted mixed crystals. When this composition of the mixed crystal is reached, crystal and melt will remain in the same layer, the liquid no more rising. A condition for equilibrium is, however, that at the same density of mixed crystal and of melt, also chemical equilibrium between mixed crystal and melt should exist. This is probably the case, since the olivine rocks enclosed in the mountain chains and the olivine inclusions in the basalts all seem to have the same composition, all containing about 10% to 12% FeO. From that temperature shell on downward where an olivine containing 10% FeO is in equilibrium with the melt, i.e., from 1,800°, the composition of the sima probably will not change further.

We arrive thus at the conclusion that isostatic adjustment and orogenesis will cause a geochemical alteration of the material of the outermost portion of the earth, causing a splitting into sial and sima layers from which volcanic material is again returned to the earth's surface. During the vertical circulation of matter thus taking place the chemical components of the rocks move in an entirely different way in the lower part of the cycle from that in which they move in the upper part. In the upper part we have the separation into clays, quartz, and the formation of carbonates; in the lower portions the rock material is split and segregated into sial and sima.

THE FORMATION OF MAGMAS DURING THE DEVELOPMENT OF GEOSYNCLINES AND OROGENIC MOVEMENTS

In the preceding chapter the general geochemical consequences of isostatic adjustment in the earth's crust have been discussed. In the following the especially extreme cases during orogenesis will be dealt with.

When sedimentation commences in a developing geosyncline, the sediments are deposited on a floor of older rock, which may consist of older sediments or of a peneplained old basement complex. If the rock floor consists of older sediments these will, however, ultimately rest on an old basement complex of metamorphic crystalline schists, gneisses, and granites. If we assume that this complex of sediments and underlying crystalline schists and gneisses, which form the supporting basement of the geosynclinal sediments, has in earlier periods taken part in isostatic adjustments, it will as we have seen in the preceding discussion, have acquired a layered constitution with a sial shell on top and sima shell farther down. The upper parts of the basement of the geosyncline will therefore consist of rocks of all kinds, but those farther down will have become layered into sial- and sima-shells and their subshells.

Now it seems to be a general rule that the first volcanic rocks to appear at the surface of the sediments of a geosyncline are rocks of the "spilitic" series, pillow lavas and picrospilitic lavas. They penetrate to the earth's surface by feeder dikes, and it seems that they appear as soon as cracks in the supporting basement of the geosyncline begin to be formed. These cracks seem to reach down to the upper shell of the sima, the temperature shell where the breaking down of the hornblende silicates of the hornblende gneisses is taking place as described earlier. Of the rock masses underlying the geosyncline this zone seems to be the first which during isostatic adjustment reaches such depths and temperature zones that geochemical changes on a large scale take place. Its material breaks down partially and forms a magma rich in volatiles, which is of great liquidity and mobility and therefore easily ascends through the cracks to the surface as lavas. It appears from our present knowledge of the volcanics erupted during the early phases of a geosyncline that these liquid spilitic magmas containing much volatiles dominate strongly at certain

places; however, at some places they seem to be accompanied by smaller amounts of rhyolitic rocks which probably originate from the temperature shell where the melting of the alkali feldspars sets in. It is characteristic of some geosynclines also that basaltic rocks alternate with the spilitic, the basaltic magma probably rising through cracks that penetrated farther down through the upper sima and reached the basaltic subshell of the sima.

If we study the development of magmatic action during the formation of a geosyncline we find, however, that at a certain stage the spilitic volcanism entirely ceases and a period of intrusive igneous action sets in, resulting in the formation of large laccolithic masses of granodioritic magmas which are injected concordantly into the sediments deposited in the geosyncline.

Now how is this change to be explained? As Vening Meinesz says in his summary of the development of a geosyncline, quoted above, after a given period the horizontal compression in the crust will exceed the "buckling limit," the process resulting in a downward bulge of the rock masses forming the supporting basement of the geosynclinal sedimentation. This down-bulging brings great rock masses down into temperature zones that are at a much higher temperature than those under which the rocks were formed; probably far down into the sima shell where temperatures are sufficiently high to melt the sial rocks entirely. When large portions of all the rocks of the basement complex are thus melted down, magma masses in great quantities will be formed, which will have a composition corresponding to the average composition of the basement complex. Now Sederholm (1925) in his well-known paper on the average composition of the earth's crust in Finland, has calculated that the composition of the Archean terrane is similar to that of the average granodiorite as calculated by Daly. The granodioritic magmas, which result from the entire basement being driven down deep into the sima shell and becoming molten, will possess the high temperatures of the sima shell and contain fairly large amounts of volatiles. On account of this condition they will also possess a high amount of eruptivity, and since they will be available in large quantities they will form the principal magma of the earlier part of an orogenic period ("primorogenic granites," Wahl, 1936),

as we for instance find them in the great central batholiths of Alaska, through British Columbia and the Coast Ranges, further through the Andes of South America and down as far as Tierra del Fuego, and also as the andesite lava of the whole chain of volcanoes along this and other orogenic zones.

The production, mobilization, and intrusion of the granodioritic magmas will continue as long as the bulging down of the geosyncline takes place. But when isostatic adjustment again sets in, and the mountain range is rising, intrusion of granodioritic magmas ceases, although the ascent of andesitic magmas at the summits of the mountain range and the activity of the andesite volcanoes continues for some time longer.

During the subsequent course of the orogenesis stretching will occur and cracks will be formed, reaching far down, permitting basaltic magmas of simatic character and origin to rise. This period corresponds to the formation of the "basic dikes" (Sederholm) that are so well exhibited in the old Precambrian mountain chains.

Later, during further orogenesis, strong lateral compression again manifests itself, resulting in folding and overthrusting, whereby large rock masses are piled upon each other and deeper-lying portions are again forced downward. During this stage of orogenesis, which often gives rise to overthrusting and movement on an Alpine scale and style, the granodiorite plutons, which during an earlier stage were concordantly intruded into the geosynclinal sediments, as described above, are in their turn folded together with the surrounding sediments and afterwards appear as "older granites" (Sederholm) of the terrane. When this rock material during the height of orogenic movement in its turn is forced downward, it will, together with other rock material, reach depths where remelting and resolution of the early melting components of the rocks takes place and large quantities of potash-rich granite and pegmatite magmas are formed ("serorogenic granites," Wahl, 1936). This zone is also the zone of formation of the migmatites. Some of the granitic matter will probably not be squeezed out entirely from the original rock mass and the process may result in the formation of more or less schistose gneisses with feldspar-quartz layers between layers of the dark minerals, or the formation of "venites." The juices of granitic composition will in other cases be squeezed out of the

rock mass and on account of their small density will rise to a higher level in the orogen. The greater portion of these granitic magmas will, however, probably not travel far, but as soon as they reach rock masses no longer soft, but cracked and schistose, will be sucked up between the layers of schistose or strongly pressed rocks by capillary force or by being pressed in, "lit par lit," between the foliation planes of the schistose rocks, forming "injection gneisses."

In those cases where the whole mass by repeated isostatic adjustments in both directions moves up and down, the zone of migmatite formation in the root portion of the mountain will also move up and down, the same rock material repeatedly passing the active temperature zone. The zone where migmatite has been formed thus may pass up and down, and the uppermost limit that it reached in the rock ground may then give the impression of a "migmatite front." When the migmatitic rocks move downwards on account of isostatic adjustment or by being bulged down they will not as such remain unaltered beneath the temperature shell in which they were formed, the salic material of this temperature surface, when the rock masses pass downward, always being melted anew and rising higher.

The granitic and pegmatitic material originating from the migmatite zone will, when penetrating upward, cut both the spilites, the granodiorites (Archean "older granites" of Sederholm), and the "basic dikes," thus appearing as younger granites in the orogenic zones (Archean "younger granites" of Sederholm).

During orogenesis there thus appear four distinct magma types that in a sense can be regarded as "parental magmas" from which by subsequent differentiation other rock types branch off. We have, firstly, the spilitic rocks grading over into picrites; secondly, granodioritic magmas that differentiate to magmas covering almost the whole range from granites to peridotites; thirdly, basalt magma; and lastly, potash granitic magmas of a composition very close to the granite eutectic. These rock magmas represent the result of the downward movement of the rock-material in the earth's crust and the subsequent rise to the surface of the earth of magmas formed in depth, the whole forming a cycle of vertical circulation of matter in the earth's crust. When the rising magmas

have solidified as rocks, these again become subject to erosion and form the material for sediments in new geosynclines. The rocks of these will again be subject to orogenesis and the material again in the depths split into the four magma groups mentioned above, the vertical circulation going on and being completed once in every orogenesis in which the material takes part.

THE MAGMAS OF THE "CRATOGENS"

Orogenesis in its later phases often passes over into crustal movements of a more "cratogenic" character and such movements may also occur on either side of the orogenic belts. The igneous activity in the cratogenic zones is of a different type from that of the orogenic zones previously discussed. The magmas appearing in the cratogens consist principally of plateau basalts, of the basalts rich in olivine of the oceanic hemispheres, of the alkalic foyaitic and essexitic magmas, and of a group of mostly potash-rich granites and with them associated gabbros, norites, and plagioclase-rich rocks (the "Post-archean" igneous rocks in Fennoscandia, the granites, red rocks and associated gabbros of the Keweenawan, the rocks of the Scotch igneous Tertiary provinces, etc.).

The plateau basalts, which apparently are the rocks of this group which appear in the largest masses, originate probably from the upper zone of the lower part of the sima, whence they rise when under cratogenic conditions cracks open up to great depths.

The olivine-rich basalt clan probably takes its origin from a still deeper subshell of the sima.

The granite-gabbro associates of the Tertiary provinces of Great Britain and some of the "Post-archean" igneous rocks in Fennoscandia probably originate by differentiation from parent magmas of composition similar to the granodiorites but of a much "dryer" character. It seems as if the intermediate differentiation products, diorites and mica diorites, etc., are left out during differentiation of such magmas "dryer" than the granodioritic magmas proper, the associations granite-gabbro and granite-anorthosite being formed.

Such a development of a dry magma in which only subordinate amounts of mica and hornblende are formed can theoretically be explained by diagrams of a type similar to Bowen's diagram (Bowen, 1928, Fig. 59). A granodioritic

material from which some part of the granitic constituents has been separated by squeezing out, but which still contains orthoclase and mica would on further partial melting in a temperature zone where mica breaks down yield a magma that on differentiation splits into potash granite ("rapakivitic magma") and norite-anorthosite.

Possibly also some of the "charnockites" are more closely connected with "cratogenic" conditions than with orogenic.

There remains further the question of the origin of the alkalic rocks. As recognized long ago by Becke, the alkalic rocks are associated with the cratogens. The alkalic magmas are comparatively dry magmas, but in spite of this they show great fluidity and ability to differentiate. They therefore probably originate in deep-seated, comparatively hot regions. Several attempts have been made to explain the formation of such undersilicated alkalic magmas by chemical reaction of subalkalic magma with desilicating agents, the hypothesis of Daly that desilication has taken place on account of reaction with limestone being the most important one. It has, however, been shown that serious objections can be raised against this explanation.

It seems that a cause of the formation of alkalic, undersilicated rocks could be that the original material has been rich in mica and hornblende, the component of the micas corresponding to kaliophilite silicate acting as desilicating agent. Mica, which is stable at fairly high temperatures, when sufficient amount of water vapor is present, breaks down on dehydration and melting and splits into olivine and kaliophilite silicates, of which the latter at high temperatures reacts with albite and desilicates part of the albite to nepheline, while itself changes to leucite and orthoclase. The desilicating action of molten biotite and the formation of some components of alkalic rocks is demonstrated by the experimental work of Fouqué and Michel-Lévy, who on melting about equal amounts of mica and microcline obtained a product consisting principally of crystallized leucite and olivine, together with some melilite and glass. The kaliophilite silicate on reacting with the orthoclase silicate, changes to leucite and desilicates the orthoclase to leucite. Also hornblende on breaking down delivers material of alkalic magmatic composition; the "norms" of most hornblendes from subalkalic rocks containing considerable amounts of nepheline and leucite, besides the chief normative constitu-

ents anorthite, olivine, diopside, and albite. Simultaneously with the partial desilication of albite, chemical equilibria among the femic silicates are also readjusted, the resulting pyroxenes and amphiboles taking up large quantities of sodium ferric-iron silicates instead of the lime-alumosilicates contained in the subalkalic rocks.

Since biotite and hornblende are evenly distributed all through the bulk of the original rock material, their components will be present everywhere in the resulting molten magma and can therefore directly act as desilicating agents. Consequently, there is in this case no need to assume that the desilicating agent, as in the case of limestone, has been assimilated and by diffusion has been able to penetrate the whole magma mass, thereby permitting a uniform desilication and causing the formation of an alkalic magma.

Bowen has given approximate diagrams explaining the formation of nepheline from a subalkalic magma by the intermediate formation of leucite (Bowen, 1928, Fig. 64). An analogous diagram, in which we substitute the kaliophilite silicate (from broken-down mica in a dry magma) in place of the leucite silicate, would still more efficiently explain a magmatic development leading to foyaitic magmas. In a magma containing a sufficient amount of volatiles the equilibrium:

$$NaAlSi_3O_8 + KAlSiO_4 \rightleftharpoons NaAlSiO_4 + KAlSi_3O_8$$

will shift towards the left as more of the kaliophilite silicate is used up in forming mica, whereas in a dry magma, where the amount of kaliophilite silicate is augmented by the breaking down of mica, the equilibrium will shift to the right, more nepheline being formed. It is, however, not possible here to discuss further this special problem.

Also, when masses of diorites, especially mica diorite, or of andesites, which are initially free from quartz, are depressed to such depths that partial melting sets in and dehydration also has proceeded far, the melt will consist chiefly of the albite component of the plagioclases in which are dissolved the components from the broken-down micas and amphiboles, and the conditions requisite for shifting the chemical equilibrium from the state dominant in the subalkalic magmas to that dominating in the alkalic magmas will thus exist in these molten portions. By the squeezing out of such molten parts alkalic undersilicated magmas of the nepheline-phonolite clan may originate.

Just as diorites and andesites in the way described above may yield nepheline syenite magmas, gabbros and basalts would in a similar way yield certain amounts of essexitic and theralitic magmas. The residue from such squeezing out of the sodium-rich portions of diorites, if melted at greater depths, give rise to the pyroxenitic magmas that often accompany nepheline syenites and essexites. It is interesting to note that from a theoretical point of view every kind of rock material containing much biotite, or biotite and hornblende, by being depressed to a zone where the temperature is high enough to cause the melting of the rock and the desilicating reactions to take place, ought to change to phonolite magma. The greater the portion of biotite of the original magma, the richer in leucite will be the alkalic rocks thus formed.

THE ORIGIN OF PARENTAL MAGMAS

There is a strong tendency in modern petrology to attribute the formation of the different igneous rocks to a common source, a parental magma, from which by differentiation all igneous rock types are thought to have been developed. The plateau basalt magma is mostly regarded as the parental magma of all other magmas, and it has been shown by Bowen (1928) that it is possible theoretically to derive the principal types of magmas by crystallization - differentiation from basalt magma. Several objections have, however, been raised to the practical application of this principle to all petrogenetic problems. Also peridotite has been considered by some authors to be the parental magma of basalt and thus of all other magmas, and Kennedy (1933) has attempted to simplify theoretical deductions by postulating the existence of two different basaltic parental magmas, viz., a tholeiitic and an olivine basaltic.

The processes of vertical circulation of matter in the earth's crust here discussed lead to the conclusion that layers of different composition are formed in the outer crustal portion of the earth, which layers may be grouped in two principal shells, the sial and sima shells. When sublayers of the sima or sial move to deeper zones where partial melting takes place accompanied by squeezing out of magma, we have seen how magmas of different kinds are formed, and under different phases of both orogenic and cratogenic development are forced to the surface of the earth. Owing to the conditions of their forma-

tion, these magmas will mostly possess a sufficient amount of heat and liquidity to differentiate during their rise through the outer part of the earth's crust. We thus arrive at the conclusion that as a result of the chemical consequences of isostatic adjustment several principal types of "parental magmas" are generated, each in a particular sublayer of the sial, salsima, or sima, and that the generation of one parental magma, as for instance the granodioritic, is independent of the generation of another, such for instance as the basaltic. The conditions of evolution of a geosyncline, an orogen, or a cratogen are the cause of the formation and rise toward the earth's surface of each particular parental magma.

During geosynclinal development and orogenesis at least the four following different kinds of parental magmas are formed: 1, spilitic and picrospilitic magmas; 2, granodioritic and dacitic-andesitic magmas; 3, basaltic magma; and 4, granitic magma. Under cratogenic conditions we obtain further 3, basaltic magmas of which the "tholeiitic" probably originate from the upper zones of the sima and the "olivine basaltic" from somewhat greater depths; 4, granitic magma, differentiating into potash granite and gabbro-norite-anorthosite; 5, charnockitic magmas, differentiating into hypersthene granite, hypersthene syenite and hypersthene diorite and norite; and 6, foyaitic magmas, by differentiation giving a wide range of alkalic magmas. From the lower part of the sima shell, 7, peridotitic and pyroxenitic magmas originate. All these magmas may be considered as parental magmas, which by further differentiation give rise to the large number of igneous rocks met with.

During this discussion it also becomes clear of what fundamental importance for the further development of the different magmas the previous dehydration and the degree of "dryness" of the parental magma is. It cannot be too much emphasized how fundamentally important for the trend of magmatic development the formation of the mica and hornblende silicates is. Until the important research work on silicates containing volatiles, now being conducted at the Geophysical Laboratory of the Carnegie Institution, has proceeded further there seems to be little possibility of giving an adequate and quantitative description of the evolution of the magmas crystallized under abyssal conditions.

THE ORIGIN OF METASOMATIC FLUIDS IN THE BASEMENT COMPLEX

Earlier it was pointed out that in a certain zone of the upper sima a large amount of rock residue rich in hornblende and mica will occur and after partial melting will furnish the material to form the spilitic magma. But when rock masses containing hornblende and mica, by isostatic adjustment or by bulging down, approach or reach this temperature zone certain amounts of the volatiles will necessarily escape even before the actual melting of the silicates. Also portions of the volatiles in the supercritical state may separate as supercritical fluids not soluble in the silicate magma portions and will travel upwards in the basement complex of rocks. All these fluids will be able to cause intense chemical changes of "pneumatolytic" character.

Recent investigations on the sedimentation in high pressure turbines, an engineering problem of considerable importance, have shown that water vapor at high temperatures in the supercritical state takes up and can hold surprisingly large quantities of iron-sodium-silicates (acmite) and also of sodium and aluminum silicate (Burkhardt and Imhoff, 1947; Morey, 1942). The occurrence in teschenites of chlorite crystallizing later than analcite (Campbell, Day, and Stenhouse, 1932), clearly shows that water vapor at high temperature dissolves also large quantities of magnesium and iron silicates.

Isostatic and orogenetic movements will thus produce also large amounts of the volatile agents responsible for the metasomatic processes in the earth's outer crust.

THE ORIGIN OF SIAL AND SIMA

We have seen above that isostatic adjustment and orogenic downwarping of the rocks of a geosyncline and its supporting basement rocks will result in the partial melting at certain depths of the easiest melting portions of the rock foundation, the feldspars. This molten feldspar will dissolve certain amounts of water vapor and also of quartz and of a small amount of the femic constituents of the rocks. Magmas of granitic composition will thus be formed. These magmas will be much less dense than the remainder of the rock foundation and will therefore rise and travel upward. Granitic rocks and magmas, therefore, can exist in the outer crust of the earth only above a certain temperature surface and it is physically

and chemically quite impossible that granite magmas should invade the outer parts of the earth's crust from deep down in the earth as generally has been the view earlier held by geologists. That the granites when brought to a sufficient depth in the earth's crust will entirely melt and be regenerated as magmas has especially been advocated by Sederholm (anatexis, palingenesis) and views related to those expressed in the present paper have earlier been published by Wahl (1918, 1936, 1943), von Wolff (1928), Eskola (1932, 1936), Holmes (1932), Kennedy and Anderson (1938), Stille (1939). Lately also Daly (1943) has recognized that granitic magmas cannot exist in the earth's crust below a certain depth. The ideas expressed in the papers mentioned above have, however, not been connected with the problems arising out of isostatic adjustment and the resulting vertical circulation of matter, and I think it is evident from the preceding discussion how intimate the interdependence of all these processes are, and that a full understanding of the formation of sial and sima is not possible without considering all these problems together.

The temperature surface in the earth's crust beneath which the melting of the alkali feldspars takes place represents therefore also a dividing surface in the earth's crust above which the granite material accumulates. This surface thus represents the bottom of the "sial layer." Since there is a difference of about 125° between the melting points of orthoclase and of albite in the presence of water vapor, the melting of the alkali feldspar components of the rocks will actually take place in a temperature shell of about 4000 m. thickness, the geothermal gradient here being taken as 30° per kilometer. We may approximately calculate the position of this zone from the melting points of albite and orthoclase and their mixtures. From the data in Goranson's investigations (Goranson, 1931, 1938) we arrive further at the conclusion that an albite-orthoclase-quartz mixture of granitic composition, saturated with water vapor, becomes liquid at about 800° to 925°. From these data we estimate a depth for the lower bordering surface of the sial of 27 to 31 kilometers. Under the influence of unilateral pressure and shearing the local melting of the early melting components of the rocks may, however, take place at much lower temperatures, i.e. at higher levels in the earth's crust, and the zone of formation of migmatites and granitic magma will under such conditions be extended

upward to higher levels. Also the thickness of the sial shell in different parts of the earth must vary according to the variations of the geothermal gradient and be different under continental areas and orogenic belts. From earthquake data it has been assumed that the sial layer below mountain ranges continues downwards to a depth of 35-40 km. (Gutenberg, 1943, 1945), but in other parts of the earth's crust may be considerably thinner (down to 20 km.).

The portions of the rock material remaining after the granite components have been expelled, principally consisting of femic components of the rock foundation, will in zones farther down in the earth's crust have to adjust themselves to "facies" that are stable at the higher temperatures and pressures prevailing there. We may regard the "sima" shell as having been formed by these rock residues and, as we have seen above, such a sima shell must consist of different layers. The outermost of these layers still containing plagioclase of intermediate composition and minerals of the hornblende and mica groups should perhaps more correctly be regarded as a separate "salsima" shell corresponding to Gutenberg's "intermediate layers" (Gutenberg, 1943).

The sima proper, beneath the "salsima," will also be composed of subshells, the outermost being of basaltic character underlain by pyroxenitic and peridotitic subshells. With regard to the thickness of the "salsima" and the outer shells of the sima, these will vary with the geothermal gradient in different parts of the surface of the earth. The peridotitic shell, as explained earlier, will probably at a certain depth acquire a constant composition, the olivine there containing about 10% to 12% FeO. Olivine of this composition is at ordinary pressure in equilibrium with its melt at a temperature of about 1780°. This temperature, however, will be raised by pressure to about 1900° to 2100°, corresponding to a depth of 65-70 km. Gutenberg gives the depth of the Mohorovicic discontinuity as at 55-65 km. beneath mountain ranges and as low as 40-50 km. under the continents. From here downward to a considerable depth the velocity of the longitudinal wave remains constant at 8.0 km./sec. This figure corresponds to the figure for peridotite obtained experimentally, and we are thus entitled to assume that from here to great depths the sima shell has a constant chemical composition and consists of olivine and molten olivine in equilibrium, the molten part perhaps

being of rigid glassy nature, in view of the high pressures prevailing at these depths. The conception arrived at here as to the constitution of the sima shell differs considerably from that proposed by Eskola (1936), but approaches in many respects the views of Gutenberg and of Daly, as set forth in Daly's latest publication (1946).

THE PROBLEM OF THE ORIGINAL CRUST OF THE EARTH AND THE LAYERING OF THE OUTER PORTIONS OF THE EARTH

Before concluding this discussion I should like to consider briefly the problems, have the sial and sima shells been developed by layering of the material before the outermost crustal portion of the earth had solidified or have these shells been formed later, and of what kind of material was the original crust of the earth formed?

The process of vertical circulation of matter in the outer part of the earth's crust, as outlined in this paper, shows that rock material of very different kinds is split into sial and sima and added to these layers. At least part of the sial and sima shells of the earth's crust have, therefore, been gradually developed out of various rock materials during the geologic history of the earth and these shells are thus not necessarily formed by layering of the original molten material of the earth.

In a paper on the Chemistry of the Meteorites the present author concluded that the chondritic meteoritic stones were formed as tuffs constituting the first "crust of solidification of a cooling cosmic body." It was pointed out that if surface conditions had been similar to those on the sun, at a later stage of development than the present, tuffs containing chondrules might be precipitated from the hot atmosphere onto a surface that was beginning to crystallize, and that deeper, beneath these surface layers, the molten material might crystallize as rocks like the various kinds of "achondrites" known (Wahl, 1910). Recently Daly has published an extensive paper on "Meteorites and an Earth-Model" (Daly, 1943).

Most petrographers who have studied the chondritic stony meteorites, which form about 80% of all stony meteorites, agree that these meteorites are of a character similar to volcanic tuffs and tuff breccias. The friable spherulitic chondrites, which are very numerous and consist of tuffitic assem-

blages of chondrules, mineral fragments and fragments of silicate glass, represent probably a primary stage of development, from which the more "crystalline chrondrites" and brecciated and veined chondrites have developed by various kinds of metamorphic processes. The principal changes seem to have been brought about by heat effects causing a partial sintering and an increase of crystallinity, and such alteration of friable chondritic matter into crystalline chondrites has been reproduced by prolonged heating of pieces of the chondrite of Bjurböle to temperatures not quite reaching the melting points of the constituents (Wahl, 1910).

If we assume that the original crust of cooling of a cosmic body like the earth was not a kind of gneissose granite, as often pictured in early geologic literature, but consisted of accumulations of chondrums and mineral and glass fragments constituting chondritic tuffs, grading downward into more "thermo-metamorphosed" material such as the "crystalline chondrites," and still farther down to crystalline material like the achondritic meteorites, the "chassinites," "chladnites," "rhodites," and meteoric "eucrites," which in structure resemble terrestrial ultrafemic rocks like peridotite and eucrite, can we explain the formation of sial and sima out of such meteoritic material?

The stony meteorites consist principally of magnesium and iron silicates, but according to the calculations of the average composition of all stony meteorites recently published by Brown and Patterson (1947-48) they contain 3.45% Al_2O_3, 2.90% CaO, 1.10% Na_2O, and 0.25% K_2O.* The chondritic stony meteorites thus contain so much aluminum and alkalies that conceivably these constituents, together with part of the lime, magnesia, iron oxides, and silica, enriched and separated from the main bulk of magnesium and iron silicates, could yield sufficient material to form a sial shell. If we estimate that four or five parts of a chondrite of average composition can yield one part of sialic composition, that is, of granodioritic composition, this seems to suffice for the production of the material of the sial shell.

* Unfortunately, our present knowledge of the average composition of the stony meteorites still remains rather inadequate. More exact knowledge can be attained only after a sufficient number of trustworthy analyses of meteorites belonging to the different groups of the stony meteorites is available and a weighted average is calculated, taking into account the number of falls in each group.

The sima and sial shells could gradually have been developed from a primary crust of chondritic composition as soon as the earth had cooled below the critical temperature of water, enabling water to be condensed from the atmosphere, and erosion and decomposition of the rocks at the surface of the earth had begun. In due time compression and movements in the crust would have set in and present conditions of vertical circulation would have developed. Gradually quartz and clays would have been formed at the surface together with carbonates of magnesium, iron, and calcium. This material, together with the remaining chondritic, would then, when the formation of geosynclines began, have been moved down to sufficient depths and by partial melting, in the way described above, magmas like our present ones would have been formed. These would in part have risen to the surface, the sima material remaining below, and in this way, as soon as the present type of weathering at the earth's surface and the formation of geosynclines had set in, a change of matter from the chondritic conditions to the present ones would also gradually have set in and sial and sima been developed. If evolution in the outer parts of our planet was of this type, it seems possible that beneath the sima portions of the meteoritic type of matter may still remain. The age of the crust of our earth is already so great that there is little doubt that the change from original meteorite material in the crust to present material has had time to proceed far and yield the present quantities of sial and sima.

According to these views the outer portion of the earth has consisted of a "crust" formed of meteoritic chondritic tuffs. Only later during geologic evolution has this crust as the result of geologic processes and the vertical circulation of matter acquired its present layered constitution, and sial and sima and the rock magmas and rocks now found in the outer portions of the earth been formed.

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PROCESSES OF EROSION ON STEEP SLOPES OF OAHU, HAWAII

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ABSTRACT. The small particles of weathered rock debris derived from the lava flows and associated pyroclastic rocks of the Koolau Range, Oahu, Hawaii, are transported from the mountain slopes of the Range to the main streams below by the processes of soil flow and soil creep. The particles are moved slowly and progressively down through the ravines and across the cliffs of the leeward theater-like valleys, and over talus-veneered bedrock slopes to the valley floors. The occasional mud flows that break out through the forest vegetation contribute to the soil flow.

Variegated patches of old thick soil, maturely developed soil, youthful thin soil, or bare bedrock on the 70-80 degree slopes at the head of one leeward theater-like valley are considered evidence of avalanching and are important in the recession of these steep slopes. A cycle of recurrent sliding is suggested, similar to that postulated by Freise for steep slopes in the Brazilian tropical forests. This cycle includes the development of soil on the 70-80 degree bedrock slopes with the establishment and growth of plants, eventual soil exhaustion after maximum use, instability induced by rainfall, and avalanching with exposure of the bedrock again.

INTRODUCTION

KOOLAU Range forms the eastern mountain mass of Oahu, Hawaii (fig. 1). Basaltic lavas and associated pyroclastic rocks of the range are built up in continuous succession into an elongate volcanic dome. The western side of the island is composed of an older volcanic dome, the Waianae Range. The two mountain ranges merge in a low, saddlelike plateau. Secondary cinder cones, lava cones, and ash cones along the south shore and inland constitute the more recent features of volcanic activity on the island. Further geographic description is not necessary; adequate accounts are found in Stearns and Vaksvik (12),[1] and Wentworth and Winchell (17).

Much of Koolau Range has undergone severe erosion and very little, if any, of the original surface of the volcanic dome remains. A few highland flats near the summit divide may reflect an original surface, and possibly several gently sloping, triangular facets on the southwest side of the Range may represent in a geomorphic sense the original flow slopes (13, p. 8-9; 17, p. 55). Waianae Range is much more extensively dissected throughout.

A great cliff extends along the northeast or windward side

[1] Numbers in parentheses refer to references at the end of this paper.

of Koolau Range from the southeast tip of the island north to Kahana Valley, a distance of approximately 25 miles. This cliff or precipice probably owes its existence to a combination

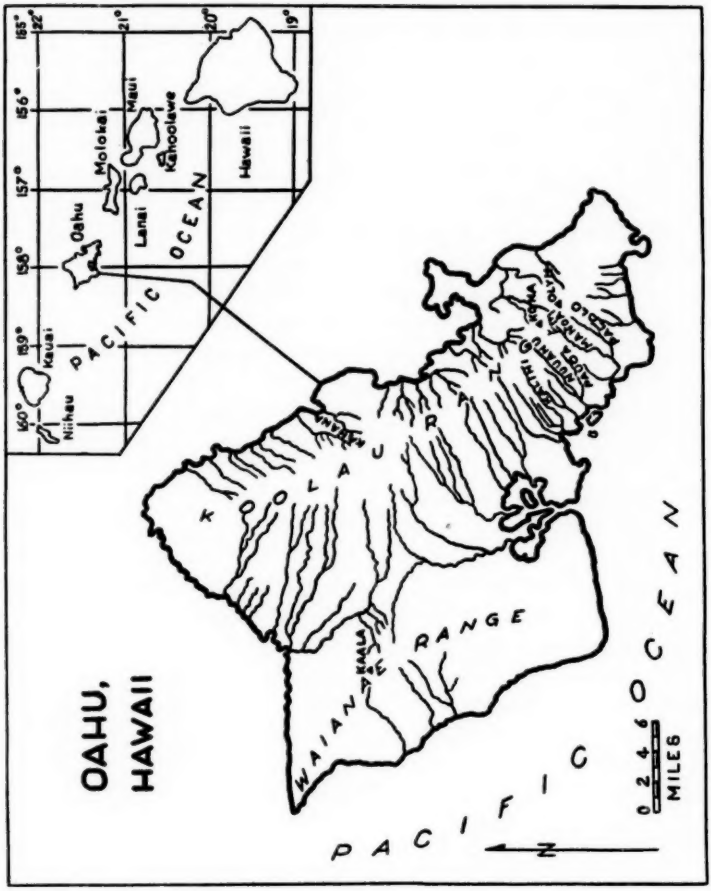

Figure 1. Index map of Hawaiian Islands, and map of Oahu, Hawaii. Kalihi Valley, Nuuanu Valley, Pauoa Valley, Manoa Valley, Palolo Valley, and Kahana Valley are indicated. Kaala—Mount Kaala, 4025 feet, is highest peak of Oahu and of Waianae Range; Kona—Puu Konahuanui; Olym—Mount Olympus.

of processes of erosion which include (1) extensive headward erosion in stream valleys aided by relatively greater amounts of rainfall at higher altitudes, (2) capture of ground water from the southwest side of the divide of the Koolau Range by the deeper eroding northeast side streams, (3) steepening and possible undercutting of steep slopes and cliffs by springs,

(4) landsliding and soil avalanches, (5) coalescing of valley headwalls into one irregular, crenulated precipice, (6) removal of narrow residual spurs between valleys by marine abrasion following submergence, and (7) emergence leaving broad, flat valley floors and some valleys deeply filled with sediments (12, p. 28-29 and Pl. 8). On the southwest or leeward side of Koolau Range, however, no such great amount of erosion has occurred. There, some of the valleys were eroded so deeply, to a base level lower than the present, that their bottoms and lower sides are aggraded to form an apparent U-shaped valley. Others, cut less deeply, are correspondingly less wide and lack the aggradational features in the bottom, and appear V-shaped (16).

A study of the processes of erosion on the steep slopes at the heads of several great theater-like valleys on the leeward side of Koolau Range constituted the main purpose of the field work presented by this paper. For possible comparison by the reader with other semitropical and tropical regions, a brief discussion of the climate, vegetation, and soil of Oahu is first reviewed. Description and discussion of the origin of the theater-like valleys is included.

ACKNOWLEDGEMENTS

The writer wishes to express his indebtedness to Dr. Kirk Bryan of Harvard University who first called his attention to the general lack of precise knowledge concerning slopes in tropical regions during a series of lectures in 1940. Dr. Chester K. Wentworth of the Honolulu Board of Water Supply has kindly reviewed this paper, and Mr. Charles E. Stearns of Tufts College has read the manuscript and made various suggestions for its improvement. The original field work was conducted while the writer was stationed on Oahu in 1944; discovery at a later date (and subsequent study) of the publication *Soil Avalanches on Oahu, Hawaii*, by Wentworth, a paper which largely anticipated the writer's field work, has stimulated this publication.

CLIMATE

The Hawaiian climate, generally speaking, is dominated by two elements: trade winds and orographic rainfall. Winds blow more than 80 per cent of the time from the northeast and

east. Uniformity of temperature is especially noticeable. Altitude continually controls both temperature and precipitation.

The North Pacific subtropical anticyclone is the immediate source of the trade winds. These oceanic winds, however, are relatively stable when they reach the Hawaiian Islands, are of shallow depth and give little rain; the effects of orographic lifting are the cause of precipitation. The majority of rain showers are heavy, most intense over mountains, some quickly dying away to leeward, others general over both islands and ocean. Cyclonic fronts, however, produce the most changeable weather, known by the Hawaiian word *kona* for leeward or southwest, and the islands' winter rainfall maximum. Kona weather is characterized by rain-producing fronts of short duration associated with high humidity and southerly winds, often followed by heavy precipitation; coastal regions on the southwest sides of the islands are most affected (9, pp. 29-51).

Figure 2 shows the distribution of rainfall on Oahu, taken from Carson (2). Average annual rainfall on Koolau Range varies from less than 30 inches to more than 300 inches. Part of Waianae Range lies in a rainfall shadow caused by Koolau Range. The amount of rainfall on Koolau Range increases with altitude, and with distance west or southwest of the Range crest. As a consequence, maximum torrential precipitation falls not upon summit crests but to leeward, as shown by figure 2. Annual precipitation for certain leeward valleys along the southwest side of Koolau Range, such as Kalihi, Nuuanu, Pauoa, Manoa, and Palolo Valleys, varies from 40 to 180 inches. Rainfall along the length of any one valley also varies. For Manoa Valley, approximate annual average at the valley portal is 41 inches, in mid valley 90 inches, on the upper valley floor 176 inches, and near summit ridges of the Range 106 inches (10, p. 566). With such precipitation, main streams never run dry. Water enters the main valleys from steep tributaries by means of waterfalls and cascades, and flows from series of springs along the foot of headwalls and cliffs. The waterfalls and cascades, however, are usually ephemeral, flowing only a few hours or a few days after a rain.

VEGETATION

Rainfall is the controlling factor in the phytogeography of the leeward valleys and of the Hawaiian Islands in general.

Manoa Valley, for example, becomes progressively hygrophytic headwards (10, p. 566). MacCaughey (10, p. 569) has divided Manoa Valley into ecologic zones: (1) Valley Floor

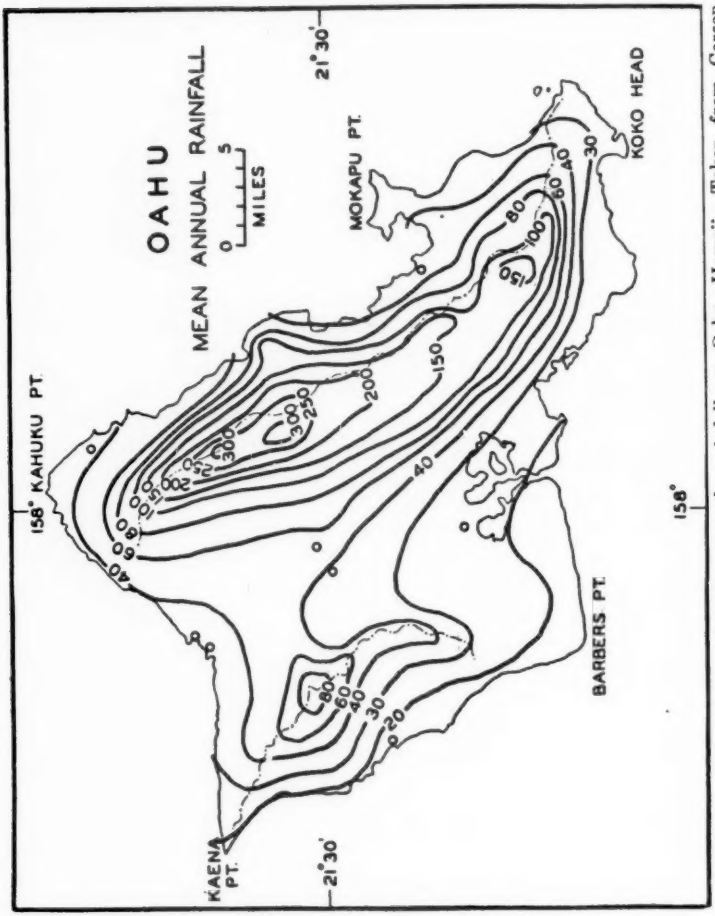

Figure 2. Distribution of mean annual ra infall on Oahu, Hawaii. Taken from Carson. Dot-dash lines represent the crests of Waianae Range and Koolau Range.

(lower floor near portal, upper floor near head), 50-300 feet in altitude; (2) Manoa Stream and its tributaries; (3) Talus zone, 100-300 feet; (4) Valley Walls or Lateral Ridges, 50-1000 feet and 1000-2000 feet; (5) Kukui zone (ravines and precipices), 300-1000 feet; (6) Koa and Lehua zone, 1000-1400 feet; (7) Hanging Valleys (rain forest), 1000-3000

feet; and (8) Summit Ridges and Peaks (including Mount Olympus, 2330 feet, and Puu Konahuanui, 3150 feet), above 2000 feet. Other leeward valleys may be divided into similar ecologic zones.

Valley floors near the heads of the valleys are heavily forested with a jungle of hau trees (*Hibiscus tiliaceus*) especially adjacent to the stream channels. Groves of the guava tree (*Psidium guajava*) are found on higher slopes, along with *Lantana camara*, *Eugenia malaccensis*, *Cordyline terminalis*, *Verbena litoralis*, and *Pandanus odoratissimus*. The steeper, upper valley walls and the walls of ravines are covered with luxuriant kukui groves (Kukui or Candle-Nut tree, *Aleurites moluccana* Willd.) which often form light green bands across the heads of the valleys. Steep slopes and precipices at the heads of the theater-like valleys support heavy shrubby growth, but may also be covered with hilo grass (*Paspalum conjugatum*). Above the kukui groves is the zone dominated by koa trees (*Acacia koa*), lehua trees (*Metrosideros collina*) and other rain forest types. Undergrowth is scanty at this altitude, consisting mainly of bryophytes and lesser species of pteridophytes (10, pp. 593-596). A few grass forms exist.

SOIL

In general, on lower Koolau Range slopes, a sublateritic soil exists in contrast with that on the upper slopes. Oxidation and relative accumulation of iron, with little soil movement, is indicated on lower slopes, whereas, with lower temperatures and greater rainfall, reducing conditions and the loss of iron are possible on upper slopes. In Hawaii, the soil absorbs rainfall and is relatively resistant to soil erosion. With a heavy forest cover, a thick soil mantle is maintained, which can stand even on very steep slopes. In the high, upland areas of Koolau Range, however, soil materials are moved so rapidly that normal soil development is rare (17, pp. 63-64).

In the lower valley bottoms, thick deposits of old alluvium are thoroughly weathered, stable, somewhat indurated, and rammed tight by weathering expansion. On high mountain slopes the alluvium is less weathered, much more permeable, and is much younger than that in the valley bottoms. Soil and mantle rock are more susceptible to slow creep and soil ava-

lanching in the mountain areas (17, p 65; 16). The chief soil masses on the mountain slopes in the heavy rainfall belt are only 10 to 30 feet thick (16); on the steep slopes of 70-80 degrees the soil is considerably thinner.

THEATER-LIKE VALLEYS

Mature looking, U-shaped theater-like valleys, eroded by consequent streams into leeward slopes of Koolau Range, are rimmed by steeply pitching ravines and precipitous walls (fig. 3). These valleys lack important tributaries. The floors of many of the valleys near the portals are flat surfaced and filled with hundreds of feet of alluvium. This partly accounts for their mature appearance. Stearns (11, p. 15) states that "Manoa Valley is a typical amphitheater-headed valley carved by stream erosion when the island stood at least 1200 feet higher than at present . . . . The flat valley floor has been produced by slow filling with silt, sand, gravel, secondary volcanic deposits, and probably coral, as the island submerged."

At the foot of ravines and precipices in the upper parts of the valleys, there are slopes covered with talus derived from the surrounding high walls. These slopes vary in width from 100 to 1000 feet, and are inclined 15 to 30 degrees from the horizontal; some approach 40 degrees. The writer believes that these are bedrock slopes veneered with talus, and not cones or fans entirely composed of talus material. Wentworth and Winchell (17, p. 55) make the following statement about similar slopes at the foot of the great cliff (or pali, meaning precipice) on the windward side of the Range: "The base of the pali is flanked by fans of debris, but in many places these apparent fans are only a veneer over buttresses of bedrock which have been left after retreat of the cliff." The talus veneered bedrock slopes in the leeward valleys may be increasing in width at the expense of the cliffs. If this is true, the erosional processes which produced the steep cliffs are no longer as operative as in the past. Blocks and boulders fill the upper courses of the streams, and appear to impede stream flow and hinder downcutting. Coarse gravel chokes the streams, but this may move during excessive rainfall.

Steep walls near the heads of the valleys are serrated by narrow, steep ravines or chutes. The walls of many of these ravines are precipitous; several are true cliffs. Cliffs rim the

heads of the valleys, a few being 200 to 300 feet high with 70 to 80 degree slopes. Above these cliffs, hanging valleys open upwards and extend back to the main summit ridges of the Range. The sides of these hanging valleys often have slopes of 45 to 65 degrees. Being in the region of heavy precipitation, the hanging valleys periodically fill with rainwater which cascades as waterfalls down the face of the cliffs below. The courses of these ephemeral waterfalls are outlined perpendicularly on the cliffs by wide zones of black, glistening water-stained volcanic rocks.

J. D. Dana, W. T. Brigham, C. E. Dutton, and C. H. Hitchcock, all early visitors to the island, described many of the topographic features and called attention to the physiographic problems involved in the origin and dissection of Koolau Range. Origin of the leeward theater-like valleys has been a source of controversy for many years. Davis (4, p. 173) observed these valleys in 1914, and stated that the great cliff on the windward side owed its origin to the retreat of weak underlying beds, and that a cliff at the head of "a southward discharging valley" probably owed its origin to the retreat of "the same series of weaker and less resistant underlying beds." Davis accompanied this discussion with a sketch of Manoa Valley (4, p. 174), reproduced here as figure 3.

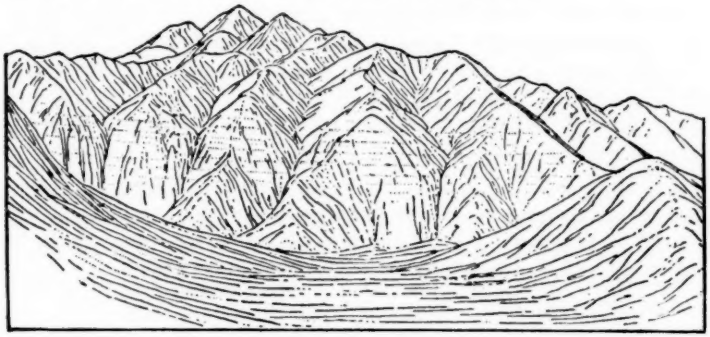

Figure 3. Generalized view of upper valley floor and theater-like head of Manoa Valley, Oahu, Hawaii. Taken from Davis. Highest peak in background is Puu Konahuanui.

Recognizing that conditions differed greatly from those in most temperate humid climates, Wentworth (14, pp. 385-410) believed that "steep-walled, blunt-headed box canyons" were

the product of normal processes of erosion for the area and enumerated as principal factors in their formation the porosity of the rocks and their tendency to weather chemically, as well as the climatic factors of high annual temperatures and rainfall. He also suggested that rapid chemical weathering near water table level allowed streams to continue undercutting headwalls and thus determine the configuration of the valleys.

Stearns (12, pp. 24-25) bases his theory for the origin of these valleys upon four conditions: (1) Streams flowing on slopes steeper than three degrees have developed amphitheater-headed valleys; those flowing on gentler slopes have not. (2) Streams undercut nonresistant beds beneath more resistant beds and form waterfalls. The alternating resistant and nonresistant beds usually dip downstream; the waterfalls "increase in height as they follow the dip upstream and tend to coalesce into one high fall." It is intimated (12, p. 25) that the waterfalls are actively incising their canyons in bedrock today. This may be true along the windward slopes of Koolau Range, and for the waterfalls in leeward valleys in the past, but the presence of hydrophytic mosses growing on the face of the cliffs along the course of the falls in the leeward valleys studied suggests the inability of the falls to incise on the face of these cliffs today. (3) Major streams as well as tributary streams erode headward into regions of high altitude and greater rainfall. The tributary streams, increased in number and in vigor, capture headwaters of streams on adjacent sides and enlarge the catchment basins of the major streams near their source, and theater-like valley heads result. The confined water in the dike complex in the interior of the Koolau dome is tapped by the more powerful streams, and this "accelerates stream capture . . . " (4) Captured hanging tributaries plunging over the cliffs produced by the waterfalls remove the narrow ridges between tributary streams by plunge pool action. These narrow ridges also are reduced by landsliding.

Stearns further suggests (12, pp. 25-26) that the valleys are oversized for the volume of water now flowing in them, but it must be rememered that under such conditions no "normal" size has ever been determined for either stream or valley. A considerable amount of talus veneers the bedrock slopes at the foot of the cliffs and occupies the floors of the upper valleys. This suggests that erosion is no longer as active as it was

in the past, and that changes have occurred which prevent streams from keeping the upper valley floors clear. If, as Stearns has specified (12, p. 26), the drainage areas above the heads of the leeward valleys have been greatly reduced by piracy from the windward side, and, if general reduction of the height of the Range of approximately 1000 feet by erosion and more than that by submergence has reduced rainfall by one half, then streams flowing in the leeward valleys are much smaller than those that once must have existed. If it can be proven that the talus veneered bedrock slopes are increasing in width, as previously suggested, then the statement that rainfall has been reduced by one half will be substantiated.

Hinds (7) and Jones (8, pp. 55-56) have called attention to these valleys, but did not advance any new explanation for their origin. Cotton (3) has presented a composite review concerning problems involved in the origin of all U-shaped Oahu valleys. He stresses need for objective study of valley sculpture in all tropical rain forest regions.

So little is known of the relative importance of processes of erosion and climatic factors that enter into the formation of these theater-like valleys that the critical reader today is still uncertain of their origin. The correct solution may be determined by conducting further field studies in the Hawaiian Islands and in tropical regions, by study of the literature concerned with similar problems of erosion in tropical climates, and by careful comparison between processes of erosion in the Hawaiian Islands and in other tropical regions.

MOVEMENT OF SMALL PARTICLES ON STEEP SLOPES

The following discussions are based upon many observations in leeward valleys on the movement of small particles of weathered rock debris down through the steep ravines and over the talus veneered bedrock slopes to the main streams on the valley floors below.

The bedrock of the leeward slopes of Koolau Range is highly permeable. It is permeable because of the great number of thin, vesicular lava flows and beds of cinders that form the Koolau dome, and also because of joints, cooling cracks, irregular contacts between flows, and lava tubes and tunnels. The interstices in these volcanic rocks are continually being

filled and flushed out with rainwater. This water, after it falls on the surface of the ground, trickles down towards the water table in the rocks beneath. As it passes through the soil, it carries some of the smaller particles of weathered rock with it. Many particles are washed into the cracks and interstices of the rocks below. Some emerge, however, after moving relatively short distances. Those particles that do emerge are deposited on the walls of the steep cliffs and ravines in the leeward valleys. Many are moved farther downhill during subsequent periods of rainfall. Those that emerge out of the rocks on the walls of ravines during a shower either are carried away immediately by the water flowing in the ravine, or, if deposited on the walls above the flowing water, accumulate as thin, reddish brown layers of mud. This mud is deposited as stalactites or incrustations of mud, and veneers the ravine walls. Depending upon shower intensity and volume of rainfall, the interstices of the rocks continue to drain for several minutes or for hours, leaving the ravine walls sheathed with mud. After the water that was flowing through the ravine has drained away, the ravine floor also becomes incrusted with mud. This accumulation of muddy particles makes ascent or traverse of ravines and steep walls not only difficult but dangerous. If the intervals between showers are long, the mud may dry and harden; then travel is easier. Another rainfall, however, cleans away the mud previously deposited; more is dropped again after the next shower. The small particles of weathered rock debris, derived from the high mountain slopes above, are thus removed and transported downward by rainwater—an effective process of erosion.

Movement of rainwater from the cliffs, ravines, and hanging valleys about the heads of the valleys results in the transfer of small particles in the form of a muddy sludge down to the talus veneered slopes below. Quantities of soil and larger rocks from the higher summits above, of course, are also washed down through the ravines to the gentler slopes below. Plant growth is relatively dense on these talus slopes; in some places large blocks and boulders rest on the slopes, but the trees, ferns, and small plants grow up between them. Beneath the plants and decaying masses of humus and forest litter and below the zone of root mats and network of rhizomes, the muddy sludge of tiny rock particles is in continual motion

during and for a short time after heavy rainfall. The mud moves downhill through the network of roots, around tree trunks and between the huge boulders that protrude above the decaying forest litter and rotting slimy humus. Travel across such slopes during or immediately after a shower is a slippery process. Occasionally the muddy particles, in the form of mud flows, break out through the forest litter and move down across the forest floor. In this manner, mud flows are spread out on top of the soil and decaying vegetation; new plant growth eventually develops on the surfaces of the mud flows and hinders any further movement. During long intervals between showers, the mud beneath the vegetation becomes dry and hard. Heavy rains soften the hardened mud and movement of the mud continues. If sufficient soil, muddy particles, and decomposed rock debris are carried out from beneath large enough areas of thick matted masses of plants, the forest is thereby lowered onto less decomposed bedrock. Further chemical decomposition will occur, and the surface of solid bedrock beneath the talus thus becomes weathered down to a lower level. Continued removal of overlying soil and weathered rock debris by flow and extrusion of the muddy particles is a valid method of slope erosion. The rate of erosion on these gentler slopes in this fashion cannot compare with that on the steeper slopes above, and proceeds at a slower rate. This flow and creep of small particles of weathered rock debris, however, is a process of erosion that trims off and lowers the talus veneered slopes. Large protruding boulders and rocks also disintegrate by chemical weathering, and are removed particle by particle. Some decayed material is removed in solution.

Perennial streams, flowing on the floors of the upper parts of the valleys between talus veneered bedrock slopes, are hindered somewhat by larger blocks and boulders that have dropped and rolled down from the steep slopes above. Most of the water in these streams is derived from the waterfalls, and from the springs that emerge along the foot of the headwalls and cliffs. A considerable amount of water, however, enters through the sides of the stream channels. This water carries with it the muddy particles that have moved across the adjacent slopes. Most of the particles are transported during heavy showers. Their appearance on the channel sides is not conspicuous during high water periods, as they are quickly swept

away. The channel walls continue to drain for several hours after a shower. They become coated with mud as the stream water diminishes in volume and no longer washes off the channel walls. During the next rainy period, the remaining mud is swept away. Accordingly, comminuted debris that has moved across the slopes above is shifted downstream.

Movement of small particles of weathered rock debris, from the higher summits and mountain slopes, down through the ravines and across the cliffs, over the talus veneered rock slopes below to the main streams on the valley floors, is accomplished by these slow processes of soil flow and soil creep. These are important, continual processes of erosion, which operate in tropical and semi-tropical regions, and cannot be disregarded in an inquiry concerning denudation.

AVALANCHING ON STEEP SLOPES

One method of erosion, not overlooked, but which has been neglected by some and considered unimportant by others, is that of landsliding or avalanching. Stearns (12, p. 25) emphasizes landsliding as an active means of erosion which should not be omitted. Wentworth (15) devoted considerable study to the process of soil avalanching with excellent results. He has pointed out its importance as a controlling factor in determination of land forms in semi-tropical mountainous regions. The writer is in full agreement with his observations and conclusions.

Wentworth ably describes abundant evidence of soil avalanching on 40-50 degree slopes; his compilation (15, p. 57) shows "80 per cent of the total between 42 and 48 degrees, with an occasional slope as high as 55 degrees." In addition to this and to the sliding on very steep knife-edge ridges mentioned by Wentworth (15, pp. 61-62), evidence of avalanching was observed by the writer on the 70-80 degree steep slopes at the head of Manoa Valley.

At a distance the steep slopes at the head of the valley present a mottled or spotted appearance. Close inspection reveals that although diversified, the steep slopes have plants in some form growing on them. Some parts of the slopes are mantled with a thick soil and well developed plant society, other parts with thick soil and stunted, scrubby grass growth. Certain other sections maintain no soil at all, but instead are sheathed

with yellow-brown mud so thin that layered volcanic cinders can be seen beneath. The soil and vegetation on the slopes are in various stages of development from youthful thin soil to maturely developed thick soil, and old thick soil. No ecologic zoning can be distinguished; distribution of variegated patches of vegetation has no obvious relation to topography or climate.

The writer believes that avalanching occurs on these steep slopes, that maintenance of the slopes has depended upon avalanching as a method of erosion in the past, and that avalanching and mass movement of particles of weathered rock debris control the recession of the steep slopes today.

Wentworth (16) believes that the surface of the bedrock and the base of the detached debris layer, with the presence of rainwater plus the indigenous weathered residuum, should be a surface of movement. He states that this is apparent because of the discontinuity of mechanical properties between the two layers. There can be no doubt that an element of discontinuity exists between the two layers, and that it is of major importance in the movement of debris. In fact, this element of discontinuity should increase when considering the steeper slopes. Avalanching also depends, however, upon the ability or inability of vegetation to aid the soil in adhering to slopes. This factor also increases when considering steeper slopes. The added weight of many plants can easily upset the equilibrium necessary for continual adherence to a steep slope. Certain types of deeply rooted trees can be most tenacious, whereas a mat of shallow rooted grasses and plants responds more readily to the pull of gravity. In addition, the weight of rainwater, suddenly multiplied, can supply the necessary impetus that sets an avalanche in motion. A thick, heavy old soil, which supports only a decadent growth of grasses, is the least tenacious. Mature soil supporting a thick mass of many plants and trees, weakened due to exhaustion of underlying soil, is very susceptible to avalanching. A youthful soil supporting young, luxuriant plant growth is the most adhesive and usually able to withstand every cloudburst.

The variegated patches of plant growth on the cliffs and steep slopes at the head of Manoa Valley and the presence here or absence there of thick soil strongly suggests that intermittent, catastrophic avalanching has occurred. The parts of the steep slopes covered by a thick, old soil which support only

grass are locations for immediate avalanching. The areas of mature soil supporting thick masses of plants and trees will avalanche in the distant future. The parts of slopes supporting a thin soil with young, luxuriant plants are locations of past avalanching and of recent soil development. The sections of bedrock sheathed with yellow-brown mud are the recently exposed volcanic rocks. Such alternate, intermittent removal of soil and vegetation and weathered rock is a method of slope recession that appears to be active today.

Recession of steep slopes in the past would certainly have been greatly facilitated by the larger drainage areas above the heads of the valleys, which are now considerably reduced, and by the higher rainfall possible during the periods of emergence and greater height of Koolau Range, as previously discussed. Any further argumentation would be pure speculation at this writing; proof of such erosion for the past will be revealed only by further field work.

CYCLES OF RECURRENT AVALANCHING IN TROPICAL REGIONS

Avalanches occur repeatedly on the face of the steep slopes and cliffs, although recurrent sliding at any one place is dependent upon many factors. These factors should include the rapidity of soil development and the establishment and growth of plant societies, the speed of soil exhaustion and decay of plant remains, and the instability of the weakened mass of soil and plant debris. A cycle of recurrent avalanching is tentatively suggested, briefly, as follows (1) fresh bedrock exposed; (2) the establishment and succession of mosses, plants, ferns, and trees to the culmination of maximum plant relationships possible, with accompanying soil development to great depths; (3) long and continued use of all available soluble minerals and organic matter; (4) final exhaustion of the soil mantle with deterioration of the plant societies, and alteration to a degenerate growth of grasses; (5) desiccation and hardening of the mass of soil, decaying litter, and rotting humus; (6) instability of the mass of debris produced during prolonged rainfall; and (7) catastrophic avalanching exposing fresh bedrock slopes again.

If the thickness of soil at the time of avalanching and the time required for one cycle of recurrent avalanching could be determined, a rough estimate for the rate of recession of such

steep slopes could be given. Wentworth (15, pp. 62-63) estimated that in a period of eight years in an area of about 15 square miles, in that part of the Honolulu watershed best known to him, an equivalent of 200 slides involving an acre each had occurred. He also estimates (15, p. 63) that an average thickness of one foot of material is removed by each slide, and that if the material is carried out of the area, that would be "equivalent to a rate of about 1 foot in 400 years for the whole area." Freise (6) in his study of Brazilian tropical rain forests postulated similar cycles of recurrent avalanching. The avalanching he describes occurs on steep slopes and cliffs of granite and gneiss. He has realized that he, too, is limited by the lack of precise knowledge as the writer, for he states (6, p. 155): "When numerical values for the progress of weathering, for erosion by disintegration, and for the rise and decline of ever-moist tropical primeval forests . . . are determined, then a figure for rate of erosion can . . . be postulated." (S.E.W., free translation) Freise's estimates for the rate of recurrent avalanching, however, of about 300-400 thousand years, do not seem to be based upon any statistical data, and cannot be considered useful at this time.

In 1940, Bryan (1) called attention to the work of Thorbecke (1927), Jaeger (1927), and Sapper (1935),[2] as well as to that of Freise (5; 6), on the retreat of slopes in tropical regions. The writer has been unable to study the works of Thorbecke or Jaeger. Sapper describes in detail processes of soil flow and soil creep similar to those that occur on the steep slopes of Oahu. Freise (5) presents his observations in the coastal mountains of Brazil with a complete description of the tropical forest cover and its effect upon the supporting soil. The processes of soil flow and soil creep that he sets forth are similar to those described by Sapper and to those presented above for Oahu. Freise also recognizes (5, p. 91) that soil flow and creep due to the delayed effects of rainwater in reaching

[2] Taken from Bryan, p. 268:

Thorbecke, F.: Der Formenschatz im periodish trockenen Tropenklima mit überwiegender Regenzeit. *Morphologie der Klimazonen* (ed. by Thorbecke). *Düsseldorfer geogr. Vort. u Erört.* Breslau, 1927.

Jaeger, F.: Die Oberflächenformen im periodish trockenen Tropenklima mit überwiegender Trockenzeit. *Morphologie der Klimazonen* (ed. by Thorbecke). *Düsseldorfer geogr. Vort. u. Erört.* Breslau, 1927.

Sapper, K.: Geomorphologie der feuchten Tropen. *Geogr. Schriften*, 7, 154 p., 1935.

the soil by way of tree trunks and their roots is a different process of soil flow than that recorded above. In 1938, he first describes the form, size, construction, and environment of "inselberge," then analyzes their origin meticulously as they developed both in the dry regions of northeast Brazil and in the constantly moist tropical coastal forests. It was in this paper (6, p. 154) that he advanced the doctrine of "erosion induces deforestation" (Erdfliessen Entwaldung schafft), and introduced a cycle of recurrent avalanching for such moist tropical regions. His cycle (6, p. 155) is summarized briefly, as follows:

"exposed granite (or gneiss) ridges — humus formation (upon a covering of lichen and small plant growth) — immigration of trees (probably leguminous at first) — development of a great primeval forest on a large scale with a combination of carbonic acid and humous acid type of decomposition — decay phenomena with soil flow and soil incrustations — atrophy of the forests to a deterioriation forest — domination and conquest by the grassy growths, destruction of the impoverished soil residue — emergence of the vegetation-freed ridges again (S.E.W., free translation)."[3]

When examined in detail, this cycle of recurrent avalanching is quite similar to that suggested for the steep slopes on Oahu. Differences in the rate of decomposition of the two types of underlying rocks, volcanic rocks in Hawaii and granite and gneiss in Brazil, make it difficult to compare what appear to be similar processes of erosion in nearly similar climatic regions. Freise's cycle, however, is much more complicated and involves a greater number of special conditions than does the one postulated for the Hawaiian Islands. Correlation between the two areas should not be attempted at present.

CONCLUSIONS

The movement of small particles of weathered volcanic rocks from high mountain summits to the valley floors by soil flow and soil creep has been recorded as observed in certain leeward valleys of Koolau Range, Oahu, Hawaii. Emphasis has been placed upon this form of erosion as a valid and important corollary to the more obvious methods of stream abrasion,

[3] Freise did not mention avalanching in this summary, probably because he discussed it at such great length in his text, but his intent is obvious.

sliding of debris and avalanching of soil. The processes of soil flow and creep are not manifest, and need to be examined and studied during their spasmodic occurrence. The avalanching on 70-80 degree slopes in one leeward valley is advanced as supplemental to Wentworth's excellent presentation of analogous features on 40-50 degree slopes. A cycle of recurrent sliding, similar to that claimed by Freise for steep slopes in the wet tropical coastal regions of Brazil, is suggested for Oahu, and includes the development of soil on 70-80 degree bedrock slopes with establishment and growth of plants, later soil exhaustion after maximum consumption, instability of soil and decaying plant debris induced by rainfall, and avalanching to expose bedrock again. Figures for rates of recurrence, especially those of Freise, cannot be considered at this writing.

With the exception of that of Freise, precise, exacting work on the erosion of slopes in tropical regions is rare. No one has come forward in the literature to attract attention to the mechanics of movement of debris on slopes in tropical regions, as, for example, has Walther Penck for humid regions. The need, however, for such an endeavor is evident; additional, accurate, discriminating field work is essential.

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THE POLAROGRAPHIC METHOD FOR DETERMINING TRACE ELEMENTS IN ROCKS AND MINERALS

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ABSTRACT. Polarographic analysis is based on the measurement of current developed in a solution contained in an electrolytic cell with a dropping mercury electrode. The magnitude of the current is proportional to the concentration of the element, and its measurement establishes quantitative determination. Identification of the element is made from the "half-wave potential," each electro-reducible or electro-oxidizable substance having a characteristic value.

The method is particularly suitable for quantitative analysis of amounts in the range of 10^{-2}M to 10^{-5}M (about .X% to .000X%), for many metals and nonmetals occurring in rocks and minerals. It offers greater sensitivity for determining Cu, Zn, Cd, and possibly other elements, than spectrographic analysis (unless special techniques are used), although it lacks the latter's advantage of multiple determinations from a single spectrogram of very small samples. Usually, not more than three or four elements are determined simultaneously with the polarograph.

In many cases, determinations can be made in the presence of other elements, which by ordinary chemical methods are impossible or impractical. Determination of many major constituents can also be made, although with less accuracy, thus permitting a quick, simple and approximate analytical method suitable for broad surveys. Outstanding applications are: simultaneous determination of ferrous and ferric Fe; Ba in the presence of Sr, Ca and Mg; Mo in ores of Mo; Cb in the presence of Ta and Sn. About forty elements are determinable.

INTRODUCTION

ALTHOUGH not well known in geochemical circles, polarography was originated about twenty-five years ago by Professor Heyrovsky, at Charles University in Prague. The analytical method is based upon the interpretation of current-voltage curves of solutions in an electrolytic cell. Under certain conditions, these curves lead to the identification and quantitative determination of one or more substances present in the solution.

The polarograph is a precision instrument which automatically records the current-voltage changes taking place in an electrolytic cell containing a dropping mercury electrode. There are three types of polarograph: Heyrovsky's original design, providing a photographic record of galvanometer deflections; a second type in which a mechanical pen produces a continuous chart record of current-voltage changes; and a third type in which a cathode-ray oscillograph acts as the recording device. The model with which data for this paper were obtained is an improved pen-recorder type (pl. 1) de-

signed by J. H. Schulman, H. B. Battey, and D. G. Jelatis (1947) at Massachusetts Institute of Technology.

A highly simplified circuit diagram of the polarograph is seen in figure 1. When a regulated voltage supply from a stor-

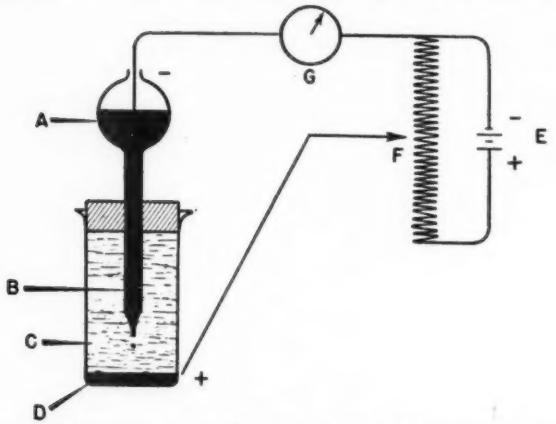

Figure 1. Schematic circuit diagram of the polarograph. *A*, Hg reservoir; *B*, dropping Hg electrode; *C*, test solution; *D*, large quiet Hg electrode; *E*, storage battery; *F*, voltage regulator; *G*, recording device.

age battery is applied to the terminals of the cell containing a dropping Hg electrode, an electric current flows through the test solution in the cell, which is amplified and recorded on the milliammeter chart.

Any electro-reducible or electro-oxidizable substance produces a characteristic curve under these conditions. Most of the metallic and nonmetallic elements occurring in rocks and minerals, as well as many organic substances, can be determined. The method is especially suitable for small concentrations, and as very little solution is needed (as little as .005 – 1.0 ml. with microcells, although 10 – 20 ml. ordinarily), mere traces can be measured quantitatively. At the Naval Research Laboratory, we have used the polarograph for determining traces of Pb, Mn, Tl and Sn in calcite and halite; and have also analyzed synthetic sphalerites for Zn and Cd as major constituents, although with less accuracy.

BASIC PRINCIPLES

The heart of the polarograph is its electrolytic, polarizing cell (fig. 2) containing a dropping Hg electrode. This electrode

is a length of glass tubing with a fine capillary opening, through which mercury from a reservoir drops slowly into the solution. The dropping electrode is generally employed as the cathode (for electro-reduction) but it is also possible to reverse the polarity of the cell and employ it as anode in the

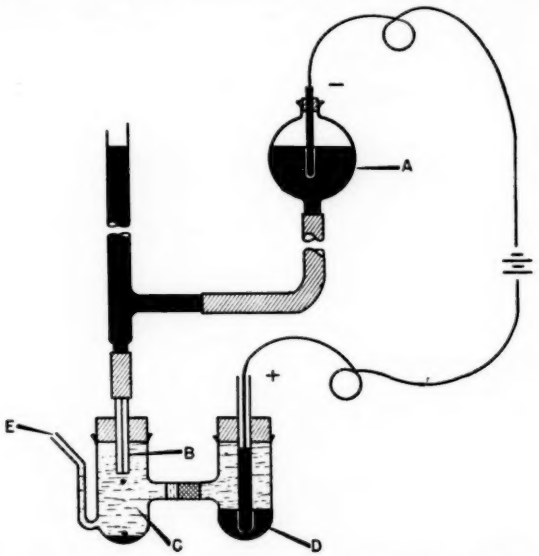

Figure 2. Dropping Hg cell with external anode. *A*, Hg reservoir; *B*, dropping Hg electrode; *C*, test solution, *D*, large Hg electrode (external anode); *E*, source of inert gas.

study of electro-oxidation reactions. The other electrode is a large quiet pool of mercury at the bottom of the cell, or an external, saturated calomel half-cell. The two electrodes are connected to a storage battery in such a fashion that a slowly increasing voltage can be gradually applied to the cell terminals. When voltage is applied to the cell, a current develops due to electro-reduction or electro-oxidation of the substance in solution.

At first, with only a small voltage supplied, the current is exceedingly small. This is the "residual current" (see fig. 3), due to minute traces of impurities always present and to capacitance effects. As the voltage is increased, a point is reached (the "decomposition potential") where there is now sufficient energy for the electro-reduction (or oxidation) reaction in

the cell to take place, and a sizeable current develops rapidly. The magnitude of the current is actually very small, rarely exceeding 50 microamperes. Finally, the current levels off, reaching a limiting value, and further increase in voltage has

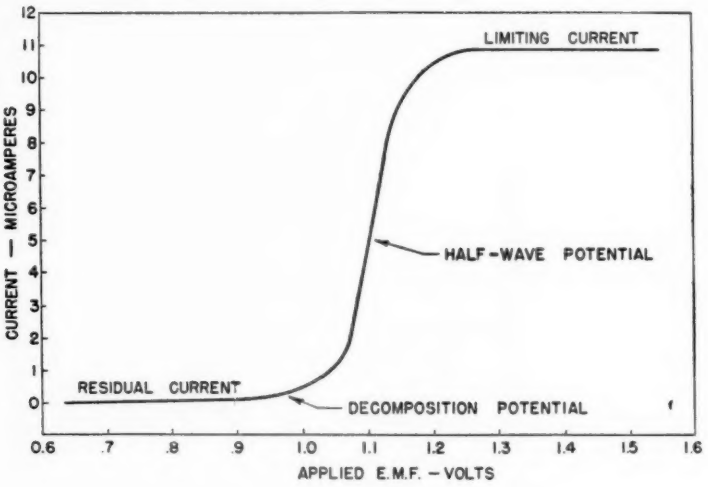

Figure 3. Typical current-voltage curve.

no effect. The net increase in current (the difference between the "limiting current" and the "residual current"), other factors being constant, is directly proportional to the concentration of electro-reducible (or oxidizable) substance in solution, and is the basis of quantitative measurement.

In order to obtain a limiting current, which is caused by an extreme state of concentration polarization (at the dropping Hg electrode), that electrode[1] must be very small and the other, relatively large. During the course of the electrolytic process, the concentration of the reducible (or oxidizable) substance is decreased near the surface of the mercury drops and, by diffusion, a fresh supply of reducible substance from the body of the solution continually reaches them. As the voltage is increased, the concentration of reducible substance at the surface of the mercury drops soon becomes so small as compared with its concentration in the bulk of the solution, that the difference approaches a constant value, and the rate

[1] A rotating, solid platinum micro-electrode is sometimes substituted.

of diffusion also becomes constant. In this sense, the limiting current is described as a "diffusion current."

The decomposition potential is characteristic of the electroreducible (or oxidizable) substance present in solution, but is also a function of its concentration, hence it cannot be made the basis of qualitative identification. Instead, the "half-wave potential" (see fig. 3) of a given substance is used for identification. This is the voltage point on the curve where the net current increase has reached one-half its limiting value, and it is independent of the concentration.

LABORATORY TECHNIQUE

The presence of a large excess of an indifferent compound or "supporting electrolyte" (one whose ions do not participate in the reaction) is necessary to ensure a limiting current that is truly proportional to the concentration. The best supporting electrolyte for a particular analysis depends largely on the substance to be determined. It is often convenient to treat a major constituent as the supporting electrolyte, such as NaCl in the analysis of halite or $CaCl_2$ for calcite (obtained by dissolving calcite in HCl). Factors to be considered in selecting a supporting electrolyte are: (1) voltage range to be covered; (2) possible formation of complex ions; (3) secondary reactions with mercury; (4) possible presence of interfering elements; (5) concentration of supporting electrolyte required (usually ranges from 0.1M to 1.0M).

Table I lists some common supporting electrolytes.

TABLE I

Common Supporting Electrolytes

1. HCl, H_2SO_4, HNO_3, $HClO_4$
2. NaCl, KCl, $CaCl_2$, etc.
3. NaOH, KOH, NH_4OH + NH_4Cl
4. Tartrates, citrates, oxalates
5. KCN, KCNS
6. Tetramethyl ammonium hydroxide
7. Pyridine + pyridinium chloride

An actual chart record, or polarogram, made with the Schulman-Battey-Jelatis instrument is shown in figure 4. The test solution contained equal amounts of Pb^{++} and Cd^{++}. When several substances are present in the solution, each one will produce its own characteristic wave on the curve, provided

that the half-wave potentials of these substances are not too close together. The over-all spread, or the height, of each

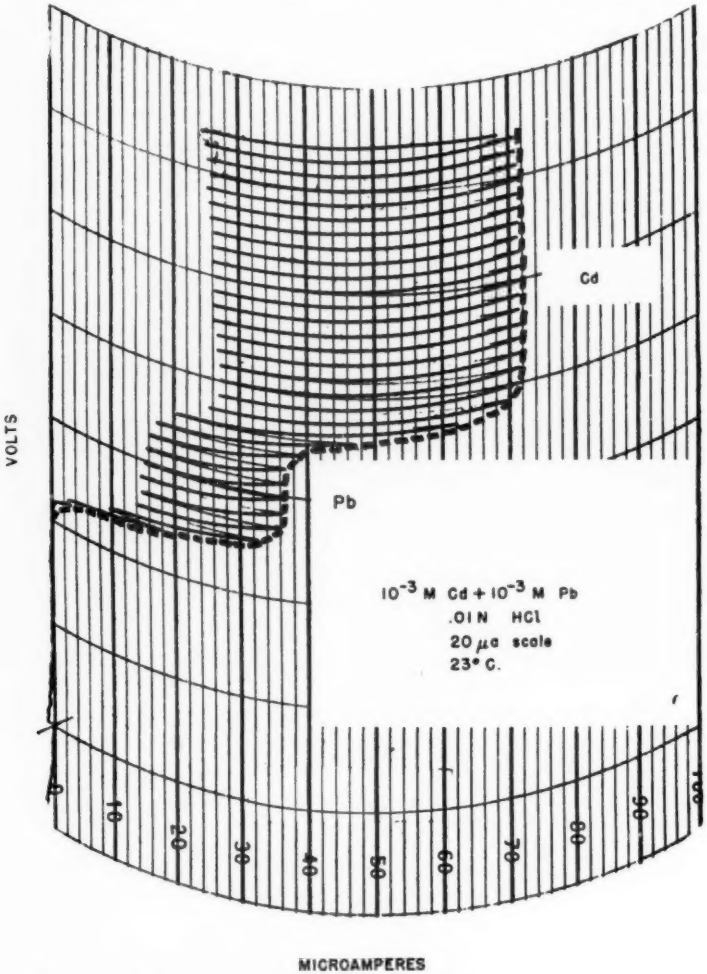

Figure 4. Polarogram of Pb and Cd present in the same solution; simultaneous recording. The heavy broken line edging the peaks has been drawn in to delineate the shape of the current-voltage curve.

wave (indicated by the horizontal portions of the outlined curve in figure 4) is measured to determine the amounts of each

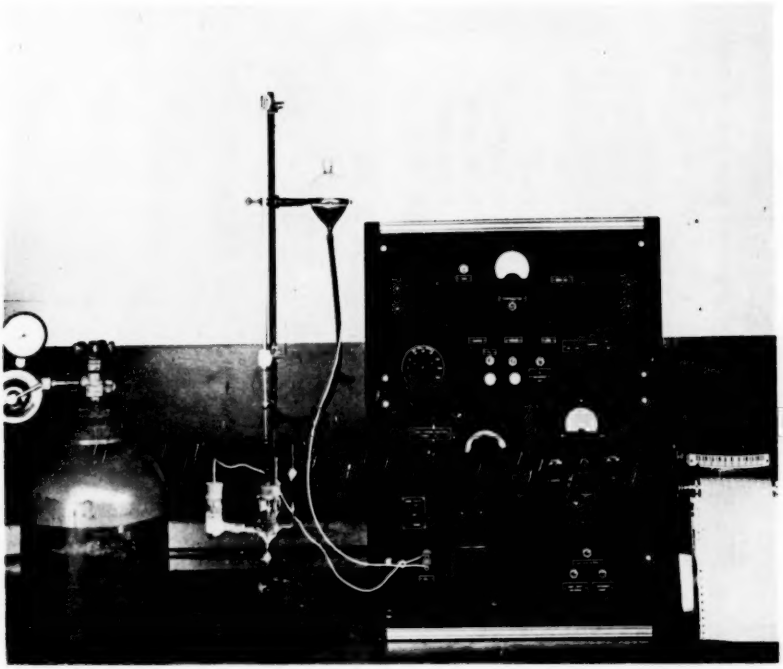

Plate 1. Naval Research Laboratory model, an improved pen-recorder type of polarograph. Reading from left to right: tank containing inert gas (nitrogen), dropping Hg cell with external anode, polarograph, recording milliammeter.

substance present. The horizontal oscillations of the polarogram (see fig. 4) merely indicate the growth and breaking

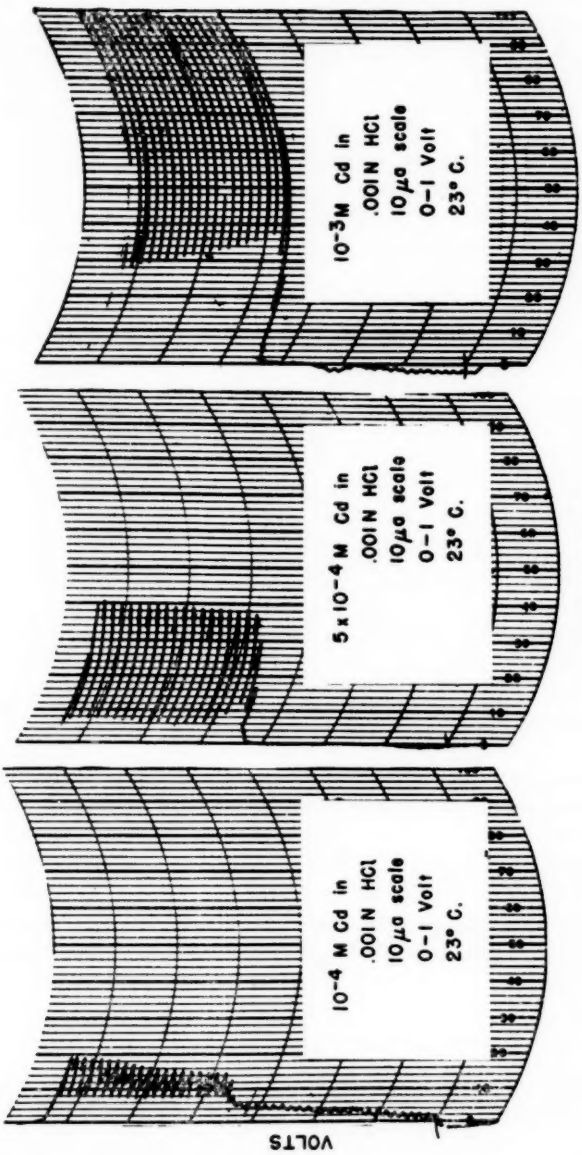
10⁻³M Cd in .001 N HCl 10μa scale 0-1 Volt 23° C.
5 x 10⁻⁴ M Cd in .001 N HCl 10μa scale 0-1 Volt 23° C.
10⁻⁴ M Cd in .001 N HCl 10μa scale 0-1 Volt 23° C.
MICROAMPERES
VOLTS

Figure 5. Polarograms of Cd, showing waves produced by different concentrations, increasing from left to right.

away of each mercury drop, and are ignored in making measurements.

In figure 5 are polarograms of Cd solutions of three different concentrations — 1×10^{-4}M, 5×10^{-4}M, 1×10^{-3}M (.01, .05, .1 g. per liter, respectively). The effect of concentra-

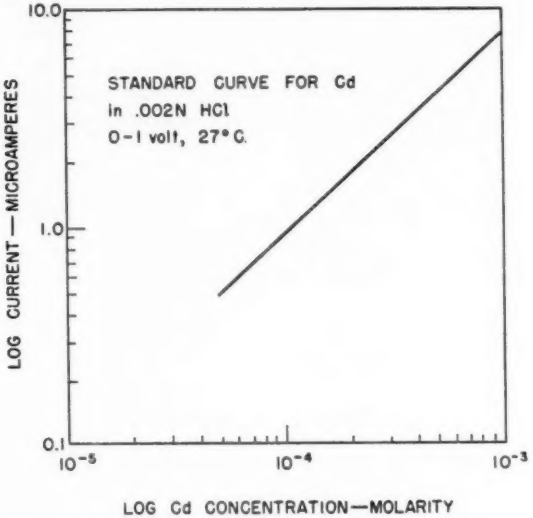

Figure 6. Standard Cd curve, for computing Cd concentration on the basis of recorded polarograph current.

tion on the magnitude of the wave, or limiting current, is readily seen.

More or less pronounced humps, or "maxima," are seen on polarograms of some substances. These tend to distort or increase the effect of the limiting current and make quantitative measurement impossible. While the origins of such maxima are complex, in practice it is usually simple to suppress them by the addition of a trace of gelatin, glue or certain dyes.

An analysis is rather simply and quickly made. The sample to be studied is suitably dissolved; the solution is placed in the cell; free oxygen (dissolved air) is always removed, by bubbling through an inert gas such as nitrogen; the current-voltage curve is recorded; the curve is then compared with standard curves (fig. 6) of known concentrations in a comparable type of solution; and the concentration of the unknown in the test sample is calculated.

Once standard curves have been prepared, these can always be referred to with reliability, provided the same dropping electrode has been employed. Temperature corrections may be necessary unless the cell is set in a constant temperature bath, or operated in an air-conditioned room. There is a 2% increase in the magnitude of the current per centigrade degree rise in temperature.

The composition of a solution about to be analyzed must be such that the ion to be measured is maintained in a definite valence state. Moreover, the wave produced when the reaction occurs must not be obscured or distorted by other nearly simultaneous reactions. For this reason, it is sometimes necessary to remove or suppress by chemical means any interfering elements. The removal of oxygen, because of its readily-developed, large wave masking other waves in that voltage range, is a case in point. It is usually sufficient to remove only the bulk of the interfering substance. Furthermore, precipitates, if formed in the process of separating out interfering elements, need not always be filtered off but can remain at the bottom of the solution, unless present in large amounts.

On the other hand, it is often possible to avoid such interferences by use of a specially selected, supporting electrolyte in the solution, or by various adjustments of the instrument itself. For example, the half-wave potential of Pb is only .06 volt more positive than that of Tl, and the two waves nearly coincide. There must be at least 0.1 volt difference between the half-wave potentials of any two substances for satisfactory wave resolution. By adding a large amount of potassium tartrate to the solution, the Pb wave is shifted away by several tenths of a volt, while the Tl wave remains unchanged. This allows for the reliable determination of Pb and Tl in the same solution simultaneously.

The polarograph permits the simultaneous estimation of several metals—sometimes as many as five or six, usually not more than two or three. Thus, where only small samples are available for complete analysis, spectrochemical examination is advisable.

GEOCHEMICAL APPLICATIONS

Geologists and geochemists unfamiliar with polarographic analysis may, at this point, jump to the conclusion that the

complex chemical nature of most rocks and minerals would cause such serious interferences as to negate the value of the method. This is not so. In Table II are listed some of the more outstanding possible applications of polarographic analysis to geochemistry. Included are certain determinations which are impossible or impractical by wet chemical methods.

TABLE II

Polarographic Determinations Applicable to Geochemical Problems

1 — Tl in presence of Pb.
2 — Pb and Cd in presence of excess Zn.
3 — Sn in presence of Cb and Ta.
4 — Cb in presence of Ta and Ti.
5 — Sb, Bi, Pb, Cd in presence of excess As.
6 — Bi in presence of excess Pb, Cd, Sb.
7 — Bi and Sb, simultaneously.
8 — Zn and Cd, simultaneously.
9 — Al, Cr and Fe-ous, simultaneously.
10 — Fe-ous and Fe-ic, simultaneously.
11 — In in presence of Zn.
12 — Ni in presence of large excess of Co, Cu, Zn.
13 — Ni and Zn, simultaneously.
14 — Co in presence of excess Ni.
15 — Rh in presence of Ir and Pt.
16 — U in presence of Th, V, Cr.
17 — *Ti in Ti-minerals (rutile, yttrotitanite).
18 — *Mo in ores of Mo.
19 — W in presence of Mo.
20 — Se in presence of Te.
21 — Se and Te, simultaneously.
22 — *Na + K in lake waters, soils, Al-silicates.
23 — Ba in presence of other alkaline earths.
24 — *Iodate traces in nitrate (Chili saltpetre).

* — Procedures already in use.

Zeltzer (1932) worked out a simple procedure for determining Ti in minerals such as rutile or yttrotitanite. The mineral is fused with $KHSO_4$ in a platinum crucible, the melt is dissolved in dilute H_2SO_4, the solution is then transferred to the cell and the polarogram recorded. Al and ferrous-Fe do not interfere, but Cr may.

Kanevskii and Shvartsburd (1940) determined Mo in ores containing from .005% to over 50% Mo, with an accuracy of 2–5%. The ore is fused with alkali flux; leached with hot water; Mn removed by peroxide treatment; H_3PO_4 is then added to an aliquot portion of the solution and the polarogram is recorded.

The polarographic waves for Na and K are so close to-

gether that only the sum of the two can be obtained. Sometimes the Na is later determined chemically with zinc uranyl acetate, and K calculated by difference. Majer (1933) developed a simple procedure for determining Na + K[3] in aluminum silicates. A very small sample is decomposed with H_2SO_4 and HF; the dried residue is treated with a drop of H_3PO_4 to precipitate Fe, Al, Ca, etc.; and tetramethyl ammonium hydroxide is added. The material, precipitate and all, is transferred to the cell, and the polarogram is recorded. This method gives an accuracy of about 5%, where the amount of Na + K averages 2% of the total. However, a complete analysis can be made in about thirty minutes, so the method may be particularly useful for broad surveys, where time and simplicity of operation are important factors.

Of the alkaline earths, only Mg cannot be determined directly at present (its wave is poorly defined). Ba and Sr, however, can be easily determined in the presence of relatively large amounts of Ca and Mg. Carruthers (1943) has developed an ingenious procedure for the indirect determination of very small amounts of Mg. The sample is treated with 8-hydroxy quinoline to precipitate Mg in complex form. The precipitate is dissolved in HCl and added to a buffer solution. The quinoline wave is recorded polarographically and then the equivalent amount of Mg present is calculated.

Cb can be determined quite readily, according to Stromberg and Reinus (1946), in the presence of Ta and Ti, by fusing the sample with K_2CO_3 and dissolving the melt in HNO_3. Sn can also be determined in the presence of Cb, Ta and Ti.

ACCURACY AND SENSIVITY

Under ordinary working conditions, the accuracy of the polarographic method is of the order of 2–5% in the usual concentration range of 10^{-2}M to 10^{-6}M, which is roughly equivalent to a range of tenths to ten-thousandths of 1%. Considering the small amounts actually involved, such an error is not unsatisfactory and compares most favorably with that of other analytical methods.

In fact, the polarograph offers greater sensitivity than the spectrograph (Claffy, 1947), unless special techniques are used, with Cu, Zn, Cd and possibly some other elements. As

[3] More exactly, this value may be the sum of all the alkali metals present, since their half-wave potentials are all rather close together.

with the spectrographic method, the sensitivity varies somewhat from element to element.

TABLE III

Periodic Chart of the Elements Determinable by Polarographic Methods‡

H																		**He**
Li	Be											**B**	**C**	**N**	**O**	**F**	**Ne**
Na	Mg											Al	**Si**	**P**	**S**	Cl	**A**
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	**Br**	**Kr**
Rb	Sr	**Y**	Zr	Cb	Mo	**Tc**	**Ru**	Rh	**Pd**	Ag	Cd	In	Sn	Sb	Te	I	**Xe**
Cs	Ba	**La***	**Hf**	**Ta**	W	Re	**Os**	**Ir**	**Pt**	Au	**Hg**	Tl	Pb	Bi	**Po**	**At**	**Rn**
Fr	Ra	**Ac**	**Th**	**Pa**	U	**Np**	**Pu**	**Am**	**Cm**								

* and rare earth elements.

‡ Elements in **Bold** type cannot be determined.

Of the 96 known elements (Table III), about 40 can be determined polarographically at present. To the writer's knowledge, the following elements of interest to geochemists are not determinable by the polarographic method: Si, P, S, Ge, Be, Th, Ta. Insofar as geochemical applications are con-

cerned, the method is still in its infancy. Much systematic investigation must be carried on to develop practical analytical procedures. With further research will undoubtedly come improved procedures to eliminate interference and to extend the method to conditions now considered beyond its scope.

ACKNOWLEDGMENT

The author is indebted to Dr. James H. Schulman, of the Naval Research Laboratory, for his advice and critical review of the manuscript.

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DISCUSSION AND COMMUNICATIONS

CHAMBER'S MINERALOGICAL DICTIONARY

In Dr. Horace Winchell's review of *Chamber's Mineralogical Dictionary* in the December number of the JOURNAL he states "Acknowledgement of the names of museums or collections containing the specimens illustrating the dictionary would be useful . . ." I should like to call attention to the fact that these illustrations appear to be taken from L. J. Spencer's "The World's Minerals" published by Frederick A. Stokes Company in 1911. In the preface to Dr. Spencer's book he states: "The forty colored-plates have been prepared under the supervision of Dr. Hans Lenk, Professor of Mineralogy and Geology in the University of Erlangen, and many of the pictures represent actual specimens belonging to the mineral collection under his charge." It would seem also from the statement of Spencer that some of the pictures of mineral specimens were not from actual minerals but were, instead, drawings.

EDWARD S. SMITH

INTERNATIONAL CONFERENCE ON QUATERNARY RESEARCH

The Fourth International Conference of the International Association of Quaternary Research (INQUA) is to meet in Budapest late this summer, from August 22 to September 15. Students in all phases of Pleistocene research — stratigraphy, anthropology, paleontology, geomorphology — are cordially invited. There will be two excursions, each approximately a week long, one to Western Hungary (Late Balaton, the Danube above Budapest), one to Eastern Hungary (eastern Hungarian plain, northern bordering mountains).

Direct circularization of interested persons has been greatly hampered by the lack of adequate lists of names, but it is hoped that as many as can will attend. Those planning to attend are requested to inform the

Hungarian Committee for INQUA IV
Hungarian Geological Institute
XIV Vorosilov-út 14
Budapest, Hungary

from whom full particulars can be obtained.

REVIEWS

Geological Explorations in the Island of Celebes; Geological Summary and Petrology; under the leadership of H. A. Brouwer. Pp. 346; 25 Pls., 25 figs., 2 fold-in maps. Amsterdam, 1947 (North Holland Publishing Co., 27.50 guilders, appr. $10.40).—This volume is a second report on the results of a geological expedition into central Celebes conducted in 1929. The first report, published in 1934 (Geologische onderzoekingen op het eiland Celebes; Verhandelingen van het Geologisch-mijnbouwkundig genootschap voor Nederland en kolonien, geol. serie, X, pp. 39-218, 1934; not seen), included a general geological summary and reports on the fossils collected. The present report is written in English.

The bulk of the present volume consists of reports on detailed petrologic studies of the rocks collected by the expedition. These reports, by W. P. de Rouver and C. G. Egeler, deal largely with the metamorphic rocks. The non-metamorphosed igneous rocks are also described though in less detail; apparently the sedimentary rocks were not studied. The rock descriptions are fairly full but not quantitative. The detailed information is well organized and is lucidly generalized on the basis of modern theories of metamorphic facies.

Preceding the petrologic reports is a new summary by H. A. Brouwer of what is known of the geology of Celebes, incorporating the new petrologic results. Unfortunately this summary is not well organized, and no clear picture of present geological knowledge about Celebes is presented. The reader wishing to learn what general results have come from the expedition must dig them out for himself, at the grave risk of making incorrect generalizations because of his lack of familiarity with the area. Professor Brouwer would have greatly enhanced the value of this work if, in the light of his great knowledge of the area, he had drawn what generalizations he could, even though they would naturally require much qualification because of the meagre data. A general map of Celebes, showing the location of the many places mentioned outside the area of the detailed maps, would also have been very helpful.

The area studied lies in central Celebes at the junction of the four great peninsulas that form most of the island (Figure 1). These four arms form two roughly concentric arcs convex northwestward. The two arcs have quite different geology and appear to represent the two geanticlinal belts which can be traced, according to several geologists, from Burma to the Banda Sea and thence through Celebes into Mindanao. The area described in this volume is apparently the only place in Celebes, or for that matter in the

East Indies south of Mindanao, where the junction between the two belts is now above water; hence its great importance and interest to students of tectonics.

The rocks of the eastern arc include a group of metamorphic rocks, now in the epidote-amphibolite facies, and a series of sedi-

Figure 1. Outline map of Celebes, showing area investigated by Netherlands Indies Geological Survey in 1929.

mentary rocks which were not affected by this metamorphism and are presumably younger. The sedimentary rocks include much limestone, some carrying *Globigerina*, some varicolored, and some strongly bituminous, and also considerable radiolarian chert. These rocks suggest deep water, but shallow water deposits are also known, including much alternating shale and sandstone (of "flysch" type, according to Brouwer), and also sandy limestone and coralliferous limestone. The deep water deposits range in age at least from Permian to middle Cretaceous; the shallow water deposits from Late Triassic to Early Cenozoic. A reader unfamiliar with Celebes cannot ascertain if the known distribution of these two facies makes any intelligible pattern.

Volcanic rocks are reported from only one area in eastern Celebes, where they are at least pre-Pliocene. However there are large bodies of ultrabasic and basic intrusive rocks ranging from peridotite (and serpentine) to quartz diorite and including many albitic types. The age of these intrusives is not certainly known, but they are reported to cut Cretaceous rocks and may be Early Cenozoic. Both igneous and sedimentary rocks are severely deformed. Although the general strike is roughly parallel to the trend of the arc, observations to date do not permit of generalizations about the force couple involved.

In central Celebes, rocks like those of the eastern arc continue westward toward the western arc, but they show progressively more metamorphism westward. This metamorphism is quite distinct from the epidote-amphibolite metamorphism of the eastern arc, on which it is in places superposed, and it affects also the sedimentary and igneous rocks that escaped the earlier metamorphism. In the lower grade eastern part of the metamorphic belt the rocks are phyllite and muscovite schist associated with some crystalline limestone and quartzite, and some of the rocks are characterized by alkalic pyroboles (esp. glaucophane) and lawsonite. In the higher grade western part of the belt, the rocks approach biotite gneiss and are characterized by potash feldspar.

Along the western side of this metamorphic belt is a fault trough called by Brouwer the median zone. It contains unmetamorphosed sedimentary and volcanic rocks of Late Cenozoic age which rest unconformably on the metamorphic rocks but are themselves strongly folded. West of the fault trough and separating the rocks hitherto described from the rocks of the western arc of Celebes is a "median line," a narrow zone of mylonite dipping steeply westward. How Brouwer interprets this line, and what its relation is to the Late Cenozoic deposits in the adjacent fault trough, is not clear from the text. The reviewer suggests that it may represent a great thrust fault, separating the rocks of the eastern and western arcs.

The predominant rocks west of the median line are metamorphic rocks intruded by large batholiths, chiefly of granodioritic composition. Though basic and ultrabasic intrusions also occur, they are minor in amount compared both to the granodiorite and to the ultrabasic rocks of the eastern arc. The metamorphic rocks show evidence of two stages of metamorphism: an older regional metamorphism chiefly to the staurolite-amphibolite and epidote-amphibolite facies, and a younger metamorphism associated with the batholiths and characterized by andalusite and sillimanite. In addition all the rocks show a late cataclastic deformation. The batholiths are also held responsible for the potash feldspar gneiss

and glaucophane schist metamorphism east of the median line. As the later of the two metamorphisms on each side of the line are thus correlated, Brouwer and Egeler suggest that the older amphibolitic metamorphisms are also to be correlated. Some rocks are reported in the western arc which appear to show only the effects of the later metamorphism.

Also present in the western arc are unmetamorphosed sedimentary rocks, chiefly sandstone, conglomerate, and shale, associated with thick volcanic and pyroclastic rocks. These rocks appear to range in age from Late Cretaceous or Eocene to Late Cenozoic. Their relation to the metamorphic rocks is not clear, but some low-grade metamorphic rocks of Eocene age are also present. Volcanics as late as Pleistocene are reported in west-central Celebes, and there are still active volcanoes at the northeast tip of the western arc. By contrast recent volcanics are unknown in the eastern arc.

If the proposed correlation of the metamorphic epochs is correct, a general geologic history can be deduced. The oldest rocks are those exhibiting the amphibolitic metamorphism; in the eastern arc this metamorphism appears to be pre-Mesozoic, but in the western arc its age cannot be determined. The next series of rocks ranges from unmetamorphosed sedimentary rocks of Mesozoic and perhaps Early Cenozoic age to the east to highly metamorphic gneisses to the west. In the east these rocks are intruded by large bodies of ultrabasic and basic igneous rocks, in the west by granodiorite batholiths. The orogenic episode represented by the metamorphism and at least the acid intrusives was mid-Cenozoic (alpine according to Brouwer). Judging from a diagram presented by Brouwer, the median line (and probably the late cataclastic deformation) were also produced at this time, though he nowhere discusses the matter. Since this orogeny, Upper Cenozoic sediments have been deposited in a number of separate basins, notably a fault trough close to the median line, and there has been great volcanic activity along the western arc. Late Cenozoic deformation occurred in the median zone and also in the southwestern peninsula of the island and perhaps elsewhere.

Brouwer compares the structure thus revealed with that of southwest Japan, where there is also a median line separating igneous and metamorphic rocks on the northwest from lower grade metamorphic rocks on the southeast (see this JOURNAL, vol. 246, pp. 57-61, 1948), and he points out both the resemblances and the differences, the latter being especially in age relations. However, one interesting implication of this comparison remains undiscussed. The older interpretation of the median tectonic line of Japan saw it as the join between two orogenic belts of different ages, but more

recently it has been considered as a great thrust fault in the core of a single orogenic belt. If the comparison with Celebes is sound, then the two geanticlinal belts that meander through the East Indies do not have quite different orogenic histories, as has generally been assumed, but are parts of a single orogenic belt, affected as a unit by the last major deformation. If so, it is amusing to note that the two belts cannot even be neatly ticketed as eugeosyncline and miogeosyncline, for one has deeper water deposits and ultrabasic intrusions, the other batholithic granitic intrusions and late volcanic activity.

The above summary of the tectonics of Celebes, extracted from Brouwer's report, is undoubtedly seriously defective in many respects, owing to the reviewer's unfamiliarity with the region and his lack of knowledge about the interrelations of the many isolated facts reported. The ideal man to prepare an adequate summary is of course Professor Brouwer, and it is greatly to be regretted that in the present volume he has not done so. JOHN RODGERS

Illustrated Catalogue of North American Devonian Fossils: Unit 1-E, part a, Family Auloporidae; edited by ERWIN C. STUMM.—This, the first unit of the catalogue to be devoted to corals, includes 114 cards and covers 91 species of tabulates assigned to 9 genera. The most prolific genera are *Aulopora, Drymopora* (which name takes precedence over *Ceratopora*), and *Syringopora.* The inclusion in the family Auloporidae of the genera *Romingeria* and *Syringopora* seems to indicate that the editor would suppress the family Syringoporidae and include the genera heretofore assigned to it in the family Auloporidae.

This unit of the catalogue is more than a mere assemblage of original descriptions and figures. The editor has revised the description where needed, in many instances has added supplementary figures, and has given the species their proper generic assignment according to present understanding.

This group was originally assigned to Drs. C. L. and M. A. Fenton, who prepared about two thirds of the cards, but the task has been completed by Dr. Erwin C. Stumm, who is now in charge of the coral group as a whole. Unit 1-E, part a, is a most welcome contribution to the Devonian fossil catalogue.

CARL O. DUNBAR

A Monograph of the Existing Crinoids; Vol. 1, The Comatulids, Part 4b, Superfamily Mariametrida (concluded—the family Colobometridae) and Superfamily Tropiometrida (except the families Thalassometridae and Charitometridae); by AUSTIN H. CLARK. U. S. National Museum Bulletin 82, 1947—This is the fifth large

quarto volume to appear as a part of "volume 1" of Dr. Clark's great monograph on the existing crinoids. Its arrangement is strictly taxonomic, continuing where part 4a left off, but its scope is far more than a mere description of genera and species.

Following a specific description these are commonly notes on peculiarities of color variation, abnormalities of form or distribution, parasites, history of discovery or other pertinent observations. The geographic and bathymetric range is indicated in all cases where it is known. The volume is a treasure house for those especially interested in existing comatulid crinoids.

CARL O. DUNBAR

The Corridor of Life; by W. E. SWINTON, illustrated by ERNA PINNER. Pp. 223, 85 wash drawings. London, 1948 (Jonathan Cape(15/-).—Dr. Swinton has admirably succeeded in his attempt to give a "simple account of the long history of living things." *The Corridor of Life* not only records the history of the inhabitants of this globe from the first beginnings of life to the present time, but also traces the main development of ideas concerning the origin of the earth and life upon it and the evolutionary principles which paleontology demonstrates.

The book commences with an adequate geologic introduction. Perhaps there is too much emphasis on methods of studying the earth's interior. Presentation of the concepts of geologic time and of modern ideas of the early history of the earth is excellent. Treatment of the principal invertebrates is more descriptive than evolutionary. Following a chapter in which vertebrates are contrasted with invertebrates and their origin discussed, somewhat over half of the book is devoted to their geologic history. Beginning with the early fishes, the trend of development is followed onto land with the emergence of the amphibians. Four chapters are devoted to reptiles (the author's special field), and the manifold adaptations of vertebrates to land, water, and air are illustrated from this group. Important mammalian types are summarized, and the evolution of horses and elephants—the two best examples —is considered in greater detail in the final chapter on "Evolution and Extinction." Here Dr. Swinton seems to favor teleological factors in evolution and to accept Broom's dictum that evolution is finished. However, in the final paragraphs, he turns this viewpoint into a strong argument for continued improvement of the human race through rational action.

The chief deficiency of this text is the omission of any discussion of fossil man and apes—a subject of great interest to the type of reader to whom such a book is addressed. There are minor inaccuracies, such as the statement that mastodons became extinct

in the Pliocene and the illustration of the evolution of the horse, which fails to agree with the correct account in the text. The reconstructions by Miss Pinner are technically accurate but unfortunately tend toward the grotesque.

In spite of occasional looseness of terminology, *The Corridor of Life* is a good introduction to the biological side of earth history. The interested layman will find no difficulty in following this story, for technical terms are carefully explained where used. The book is particularly suitable for collateral reading in an historical geology course. Except for lack of detailed illustrations of the osteology of various animals discussed, it would be quite suitable as introductory paleontology text. Dr. Swinton is to be congratulated on preparing such a readable account of life in the past. JOSEPH T. GREGORY

Vibration and Sound; by PHILIP M. MORSE. Second Edition. Pp. xix, 468; 89 figs. New York, 1948 (McGraw-Hill Book Co., $5.50).—The second edition of this successful work on acoustical theory contains a very appreciable extension of the material presented in the previous edition. A larger page area and more than one hundred additional pages effect an increase of reading material of at least one-third. The most conspicuous—and welcome—feature of the new edition is the inclusion of the theory of transient acoustical phenomena. This analysis is set forth with the aid of operational calculas, providing an excellent illustration of the utility of this branch of mathematics. The first chapter carries a brief introduction to such constructs as contour integrals and Fourier transforms, and at the end of each subsequent chapter they are applied to the subject under discussion; the material is arranged, however, to allow their omission without loss of continuity in the book. As in the first edition, the emphasis throughout is on *methods* of acoustical analysis, and the author frequently stops to review and sum up the techniques he employs.

The chapter headings remain the same in the new edition but several new details have been added, besides the treatment of transients. Thus, piezo-electric crystals, the motion of a piano string, some theory of reed and wood-wind instruments, the absorption of sound by porous walls, and the general problem of transmission through ducts are a few subjects that add to the value of the second edition. The author has clarified and emphasized the role of the concepts of mechanical and specific acoustical impedance of various types of acoustical circuit elements. The transmission of sound inside cylinders is analyzed as a wave-guide problem, a procedure which suggests the feasibility of wider application of this method to the problems in the conduction and radiation of ultrasonic frequencies. The electrical analogue which has been so suc-

cessfully exploited in acoustics gains new and greater value in the high frequency range.

On the debit side of the ledger there are very few items. The derivation of the equations of a sound wave seem awkward to this reviewer, and could profit from the introduction of the concept of velocity potential (the term is nowhere mentioned). One could also wish for some references to the literature of theoretical and experimental acoustics. A few typographical errors result from the bodily transfer of sections from the first to the second edition, but these are seldom serious enough to be confusing. Without doubt, Professor Morse has made a valuable contribution to the theory of sound. This book is a worthy shelf companion to Rayleigh's "Theory of Sound."

RICHARD F. HUMPHREYS

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